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Effectiveness of Biochar and Elemental Sulfur for Sustaining Maize Production in Arid Soils

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SANDY soils represent most of the arable lands in Egypt. These soils are infertile and therefore incorporating organic products such as biochar in their surface soil layers are recommended to improve their productivity. Yet, biochar is of alkaline nature which may diminish the availability of many soil nutrients needed for proper plant growth. Thus, the current study investigates the impacts of adding elemental sulfur together with biochar to lessen the negative consequences of normal biochar on productivity of maize plants grown on a poor fertile light-textured soil. Also, acid modified biochars with either sulfuric or phosphoric acids were used herein to attain this goal. To attain this goal, a pot experiment of a randomized block design was conducted, comprising 2- factors: (1) 3-types of biochar (non acidified (BC), acid modified biochar with sulfuric acid (SMBA) and acid modified biochar with phosphoric acid (PMBA)) mixed with a soil (loamy sand, 97% sand) at a rate of 10 g kg^{-1} as well as the non-amended-control. (2) elemental S applied at rates of 0, 2 and 4 g kg^{-1} soil. All pots received 1.6 g kg^{-1} compost then left to equilibrate for two weeks. Later, maize seeds were planted for 60 days. Results reveal that maize dry weights and heights were significantly enhanced owing to application of acidified-biochars; while the corresponding increases owing to application of non-acidified biochar were almost significant. Such increases were correlated significantly and positively with both Olsen-P and AB-DTPA-Zn. On the other hand, application of S recorded no direct significant impacts on maize growth parameters, nevertheless it decreased significantly soil-pH, especially with increasing the dose of application and this in turn upraised extractable-AB-DTPA-extractable-Fe and Zn. Interactions between non-acidified biochar and S recorded further positive improvements in nutrient availability and plant growth versus applying each soil; yet such increases were still below the ones recorded for acidified biochars. The environmental impacts for using these additives on global warming threats were also considered in this study via calculating C-cycle feedback and all estimated values were positive. This indicates that sequestered C was probably higher than its emissions. Future perspectives are needed to investigate the efficiencies of using these additives under field conditions for at least two successive seasons while evaluating the economic and environmental outcomes for these additives.

Keywords: Acid acidified biochars; Maize; Arid soils; Soil pH; Soil carbon balance; Available nutrients; Elemental sulfur.

1. Introduction

Sandy soils represent most of the arable lands in Egypt (Selim and Mosa, 2012). These soils are of poor structure (Zhang *et al.*, 2021) and exhibits weak water holding capacity (Li *et al.*, 2021). Thus, the leachability of nutrients from their top soils could be high (Yao *et al.*, 2012; Haider *et al.*, 2017) and this, in turn, diminish the productivity of plants grown thereon (Farid *et al.*, 2014; Farid *et al.*, 2021a; Farid *et al.*, 2021b). To cope with these adverse conditions, an organic product called biochar, or the black diamond (Abdelhafez *et al.*, 2017), is guaranteed as a soil additive. Biochar improves soil physical, chemical, and hydrological properties (Gluba *et al.*, 2021) because of its high surface area and porous structure (Alkharabsheh *et al.*, 2021). Besides, essential nutrients needed for proper plant growth release slowly from biochar; hence lessen their leachability from soil (Elshony *et al.*, 2019; Li *et al.*, 2021). Additionally, biochar has little impacts on emissions of greenhouse gases

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(GHGs) (Farid *et al.*, 2022). The carbon rich product named by biochar is the outcome of pyrolysis of organic residues in absence of oxygen (Farid *et al.*, 2022; Hageb, 2024; Soliman *et al*., 2024; Gyanwali *et al*., 2024), forming a condensed aromatic product of low degradation rate (Fang *et al.*, 2014; Xiao and Chen, 2017) During pyrolysis process, acidic groups such as carboxyl decline, while basic ones increase (Alkharabsheh *et al.*, 2021); thus biochar exhibits an alkaline nature (Abdelhafez *et al.*, 2021).

In arid soils, biochar application increases soil acidity consequently lessens nutrient availability in soils (Abdelhafez *et al.*, 2020). Alternatively, acid modified biochars are guaranteed (Ippolito *et al.*, 2016) using either sulfuric (Ahmed *et al.*, 2021) or phosphoric acids (Zhao *et al.*, 2017). A third option is to apply normal biochar together with elemental sulfur. This option may effectively reduce soil pH to attain more desirable pH range (El-Gamal *et al.*, 2020) beyond those attained for the non-acidified biochar (El-Gamal *et al.*, 2020; Hammerschmiedt *et al.*, 2021) in order to improve plant growth (Abd El-Mageed *et al.*, 2020). The latter approach could be more economic than acidified biochar. Thus, the main goal of this study is to find out to what extant can elemental S be effectient enough to lessen the alkaline impacts of biochar on maize grown on a poor fertile sandy soil versus amending soil with acidified biochar.

Maize is an influential component of food security and economic development worldwide (Prasanna *et al.*, 2020) besides being a valuable energy-rich feed for livestock (Hallauer and Carena, 2009). In Egypt, this is one of the most important cerial crops together with wheat and rice (Ali and Abdelaal, 2020; Farid *et al*., 2023; Sheta *et al*., 2024). Maize can be grown successfully in newly reclaimed deserts of sandy structure; however after considering appropriate organic additives to lessen the drought stress conditions (Mazen *et al.*, 2015). The current study aims at investigating the integral effects of using elemental sulfur with non-acidified biochar for boosting maize growth versus applying either sulfuric or phosphoric acid modified biochars.

This aim is not so far investigated. Specifically, it is assumed that non-acidified biochar plus elemental sulfur can enhance plant growth parameters when being used as a soil amendment beyond those attained for using the non-acidified biochar solely **(hypothesis 1).** Probably, the consequences of the former treatment (biochar+ elemental sulfur, the less inexpensive option) are comparable to those of acidified biochar (the more expensive choice) **(hypothesis 2)**. The enhancements in maize growth parameters were basically the consequences of improving soil characteristics (soil pH, EC, and residual organic carbon), especially due to application of the acidified biochars because they notably reduce soil pH **(hypothesis 3) and** have high degradation rates than normal biochar and this consequently set more nutrients needed for proper plant growth **(hypothesis 4)**, while retain lower residual soil organic carbon by the end of the experimental study **(hypothesis 5)**. Overall, biochar application probably has positive carbon cycle feedback **(hypothesis 6)**. We believe that this research may considerably improve the efficiency of using biochars in light textured soils to increase the growth of plants thereon, and at the same time, sustain the surrounding environment.

2. Materials and methods

2.1. Materials of Study

A surface soil sample (0-30 cm) was collected from Arab Agadeer area (31° 16’ 42” E and 30° 21’ N), Qualubia Governorate, Egypt. This samples was air dried, finely ground to pass through a 2mm sieve then analyzed for its physical and chemical characteristics as outlined by Klute (1986) and Sparks *et al*. (2020) and the obtained results are presented in Table 1.

Table 1. Physicochemical characteristics of the soil under study

Parameter	Value	Parameter	Value
Coarse sand (%)	86.00	Water holding capacity (%)	26.60
Fine sand (%)	1.70	EC (dS m^{-1})	3.33
Silt (%)	6.51	pH	7.20
Clay (%)	5.79	Soil organic carbon (g kg^{-1})	6.00
Textural class	Loamy sand	$CaCO_3$ (g kg^{-1})	29.90

*EC was determined in soil paste extract while pH was determined in 1:2.5 soil: water suspension

Compost was obtained from the Compost Production Unit at the Faculty of Agriculture (Benha University) and its characteristics were determined (Table 2). Seeds of maize (SC-P3444) were obtained from Pioneer International Company in Egypt.

2.2. Biochar preparations

Potato straw (collected from the experimental farm of the Faculty of Agriculture, Benha University) was used for production of biochar via pyrolysis in a muffle furnace (VULCAN D-550) at 450 C for 5 h , followed by steam activation to improve its microporosity as outlined by Khalil *et al*. (2023). Afterwards, the produced biochar was ground to pass through a 0.18 mm. One third of the produced biochar was left without acidification while the other two thirds were acidified via either sulfuric or phosphoric acid as follows:

Sulfuric acid modified biochar (SMBC): one third of the produced biochar was mixed with sulfuric acid (30 %) at a rate of 1:20, then shaken with an orbital shaker for 4 h. Afterwards, the acidified biochar was washed 5 times with distilled water, and oven dried at 40 °C (Vithanage *et al.*, 2015).

Phosphoric acid modified biochar (BMBC): One third of the dried biochar (BC) was placed in a conical flask together with HNO_3 (32.5 %) at a rate of 1:30, then the mixture was heated at 60 °C for five hours under constant magnetic stirring. Later, the sample was sieved and washed with hot distilled water until the pH of the leachate become almost neutral (Li *et al.*, 2016; Khalil *et al*., 2023)**.** Chemical characteristics of these biochars are presented in Table 2.

Table 2. Characteristics of the used organic additives

Property	Compost	Non-acidified biochar	SMBC	PMBC
EC (1:10 suspension)	4.90	7.90	3.40	4.80
pH (1:10 suspension)	7.60	8.40	3.08	3.60
Organic carbon (g kg^{-1})	197.30	288.40	242.00	297.00
Organic matter (g kg^{-1})	340.20	497.20	417.20	512.00
Total N (g kg^{-1})	7.00	3.50	4.90	4.90
Total P (g kg^{-1})	0.38	0.40	0.40	0.40
Total K (g kg^{-1})	2.10	2.30	9.2 0	6.80
C:N ratio	28.2:1	82.4:1	49.4:1	60.6:1
Total Fe (mg kg^{-1})	25.30	39.20	30.30	36.40
Total Mn (mg kg^{-1})	8.90	10.80	9.90	11.90

Note: SMBC: sulfuric acid modified biochar, **PMBC**: phosphoric acid modified biochar.

2.3. The green house investigation

A pot experiment was conducted under the greenhouse conditions of soils and water Department at Faculty of Agriculture, Moshtohor ,Benha university, Qalyoubia Governorate in the summer season of 2020-2021. This experiment followed a randomized complete block design comprising two factors: **factor A (type of biochar):** non-acidified biochar (BR), sulfuric acid modified biochar (SMBC) and phosphoric acid modified biochar (PMBC), all applied at a rate of 10g kg^{-1} beside of the no application control (No BC) and **factor B (elemental Sufur)**: applied at three different rates i.e. 0, 2 and 4 g kg^{-1}. All treatments were replicated trice.

Soil portions, equivalent to 5 kg, were mixed thoroughly with the abovementioned amendments on a plastic sheet and also 80 g of compost (a source of beneficial biota and nutrients) was incorporated within all treatments. Soil portions were then packed in plastic pots (20cm diameter ×17.5cm depth) and left for two weeks to equilibrate without planting while maintaining soil moisture (with distilled water) at 80% of the water

holding capacity to stimulate the activity of soil biota. Afterwards, seeds of maize were planted at a rate of 5 seed per pot, then thinned to 3 after germination.

Soil moisture was kept at 80%of the water holding capacity during the experimental study which lasted for 60 days, thereafter**.** plants were removed from their pots and placed on plastic tubes and washed thoroughly with a gentle current of tap water to remove stunted dirt then by distilled water. Stem diameter and heights of plants were measured in each treatment, afterward the plant materials were oven dried for 72h at 60-70 C and dry weights were determined . Also, soil samples were collected from the rhizosphere of each pot and air dried.

2.4. Soil analyses

Soil pH was determined in 1:2.5 soil water suspension using a pH meter (Jenco 6173), while EC (Electrical conductivity) was determined in the saturated soil past extract by using EC meter (Hanna EC215). Organic Carbon content was determined in soil samples following Walkley-Black method as mentioned in Sparks *et al.* (2020). Available P was extracted by Olsen then determined by Spectrophotyometer (Spectronic 20D) while the available contents of Fe and Zn were extracted by AB-DTPA according to Soltanpour (1985) then determined by Atomic absorption (Perkin Elmer Precisely Analysis t400). All the chemicals used in this study were of analytical grade and were obtained from Sigma-Aldrich.

2.5. Data processing

The obtained data were subjected to two- way ANOVA and Dunken's text via SPSS ver 18. Soil carbon balance was estimated as a difference between C outputs (sequestered in plant tissues and residual organic carbon in soil) minus C-inputs (initial C content in soil and the applied amounts of C via compost and/or biochars) as outlined by Farid et al. (2022). Figures were plotted using Sigma plot 10 software.

3. Results

3.1. Effect on the vegetative growth parameters of maize plant

Dry weights of maize plants increased significantly owing to application of the biochars, especially the acidified ones (SMBC and PMBC). Likewise, these additives boosted significantly plant heights and stem diameters (Fig 1). On the other hand, no significant effects were found for application of elemental sulfur on the abovementioned growth parameters. Concerning the interactions between biochar and elemental S, the highest increases in both plant dry weight and stem diameter were recorded for PMBC, irrespective of the rate of applied sulfur. A comparable increase in plant dry weight was found for SMBC at all applied rates of S. It is worth to mention that the stem diameters of maize plants recorded for the treatment "BC+2g S kg^{-1}" were comparable to those of PMBC. In case of plant height, no significant interactions were identified among the investigated treatments.

3.2. Effect on the different types of biochar and S application doses on soil chemical characteristics

Application of biochar significantly influenced soil pH (Fig 2A). In this aspect, the non-acidified biochar (BC) raised soil pH while the acidified ones (SMBC and PMBC) diminished this parameter with no significant variations between these two additives. Generally, biochars raised soil EC (Fig 2B, except for PMBC) and also elevated residual organic carbon (ROC) by the end of the growing season (Fig 2C). In this aspect, the highest increases in ROC were recorded for both that non—acidified biochar as well as for PMBC, with no significant differences between these two organics. Regarding the effects of elemental sulfur, increasing its application dose led to concurrent reductions in soil pH while raised soil EC. It was noted that elemental S recoreded no significant impacts on residual organic matter in soil.

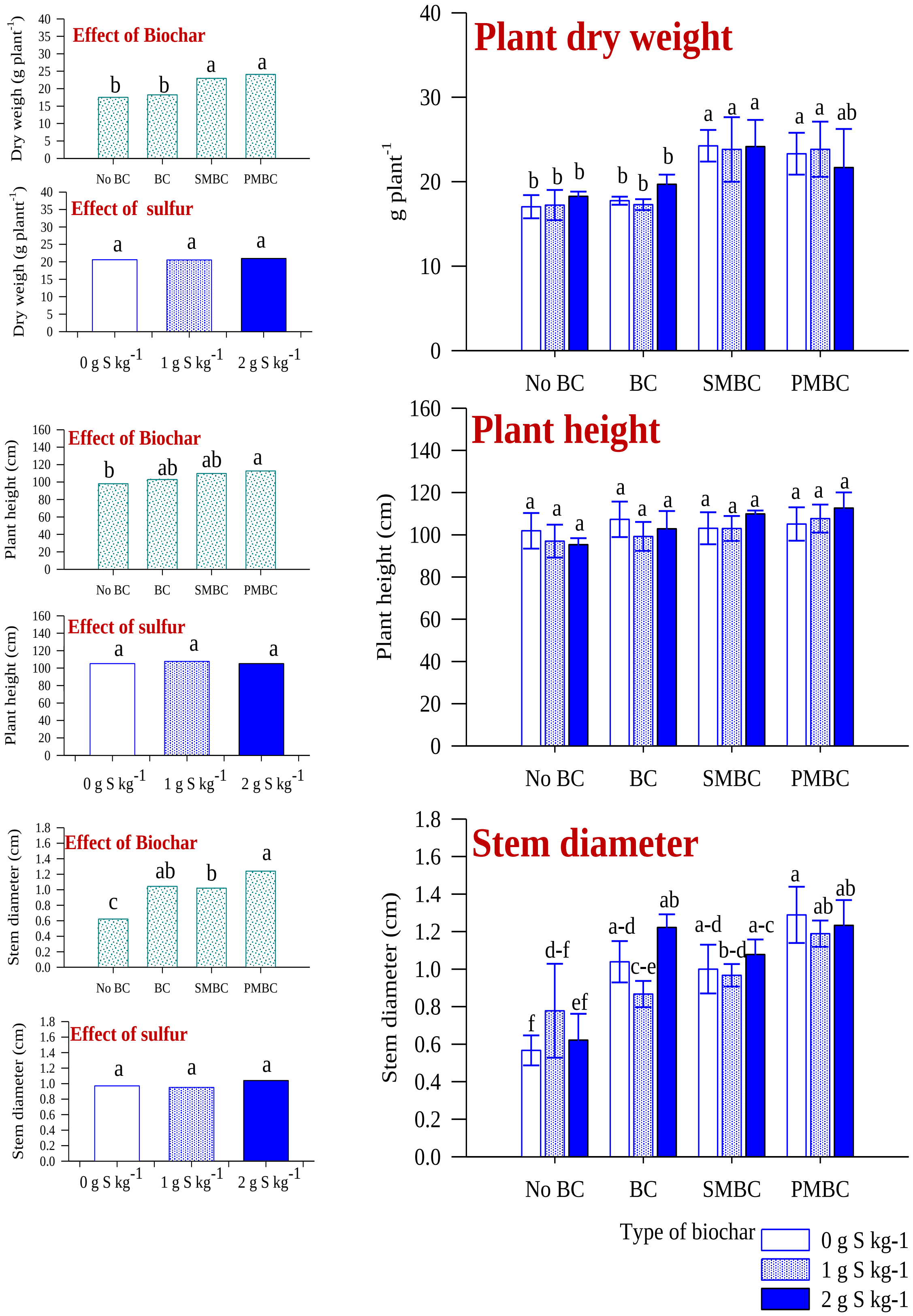

Fig. 1. Effect of different types of biochars and S application doses on the vegetative growth parameters of maize plants (mean± standard deviation). No BC: no applied BC, BC: non-acidified biochar, SMBC: **sulfuric acid modified biochar, PMBC: phosphoric acid modified biochar. Similar letters indicate no significant variations at *P*<0.05**

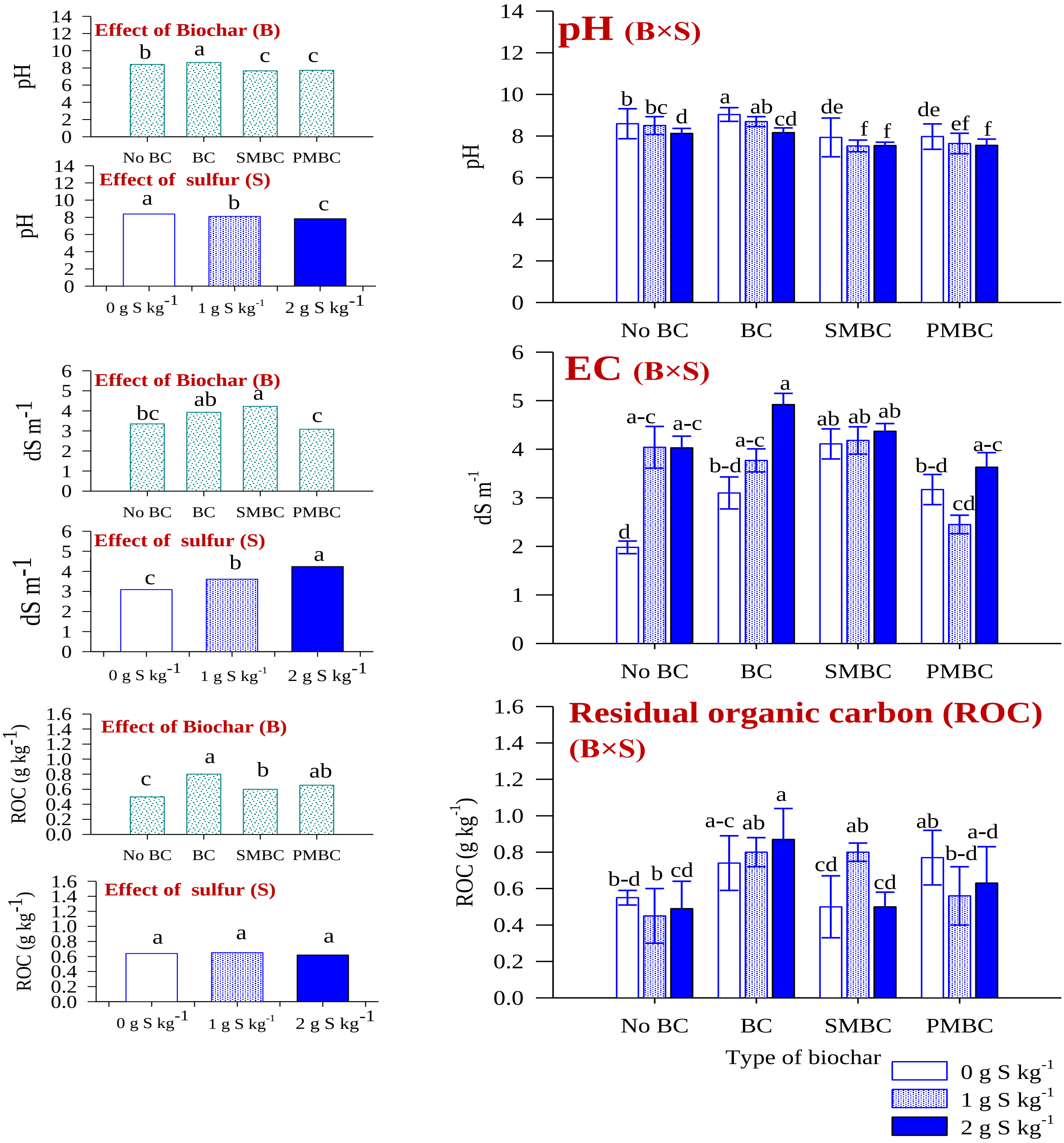

Fig. 2. Effect of different types of biochars and S application doses on soil characteristics (pH, EC and residual organic carbon) (means± standard deviations). No BC: no applied BC, BC: non-acidified biochar, SMBC: sulfuric acid modified biochar, PMBC: phosphoric acid modified biochar. Similar letters indicate no significant variations at *P*<0.05

Interaction results between these two factors (biochar×elemental S) reveal that application of elemental sulfur to the non-acidified biochar; although decreased soil pH; yet the obtained values were still higher than those obtained by acidified biochars. On the other hand, this treatment (BC), when received either 1 or 2 g S kg^{-1}) recorded the highest C stability in soil (high ROC) and also exhibited the highest EC values. Generally, acidified biochar, in presence of the high applied dose of S, displayed the least pH values. The least EC value was recorded for the non-amended control soil whereas soil EC increased considerably with the application of either biochar and/or elemental S. The highest increases in this parameter (soil EC) were recorded for the SMBC treatment (-/+S) and BC amended soil that received only 2 g S kg^{-1}.

3. 3. Effect on P, Fe and Zn available contents in soil

Application of biochar raised significantly the available fractions on soil nutrients in soil, i.e. Olsen-P, AB-DTPA-Zn and AB-DTPA-Fe (Fig 3). The highest increases in Olsen-P were found in case of BC and SMBC amended soils, with no significant variations among these two additives. On the other hand, PMBC recorded the least increases in Olsen-P , while exhibited the highest increases in AB-DTPA-Zn.

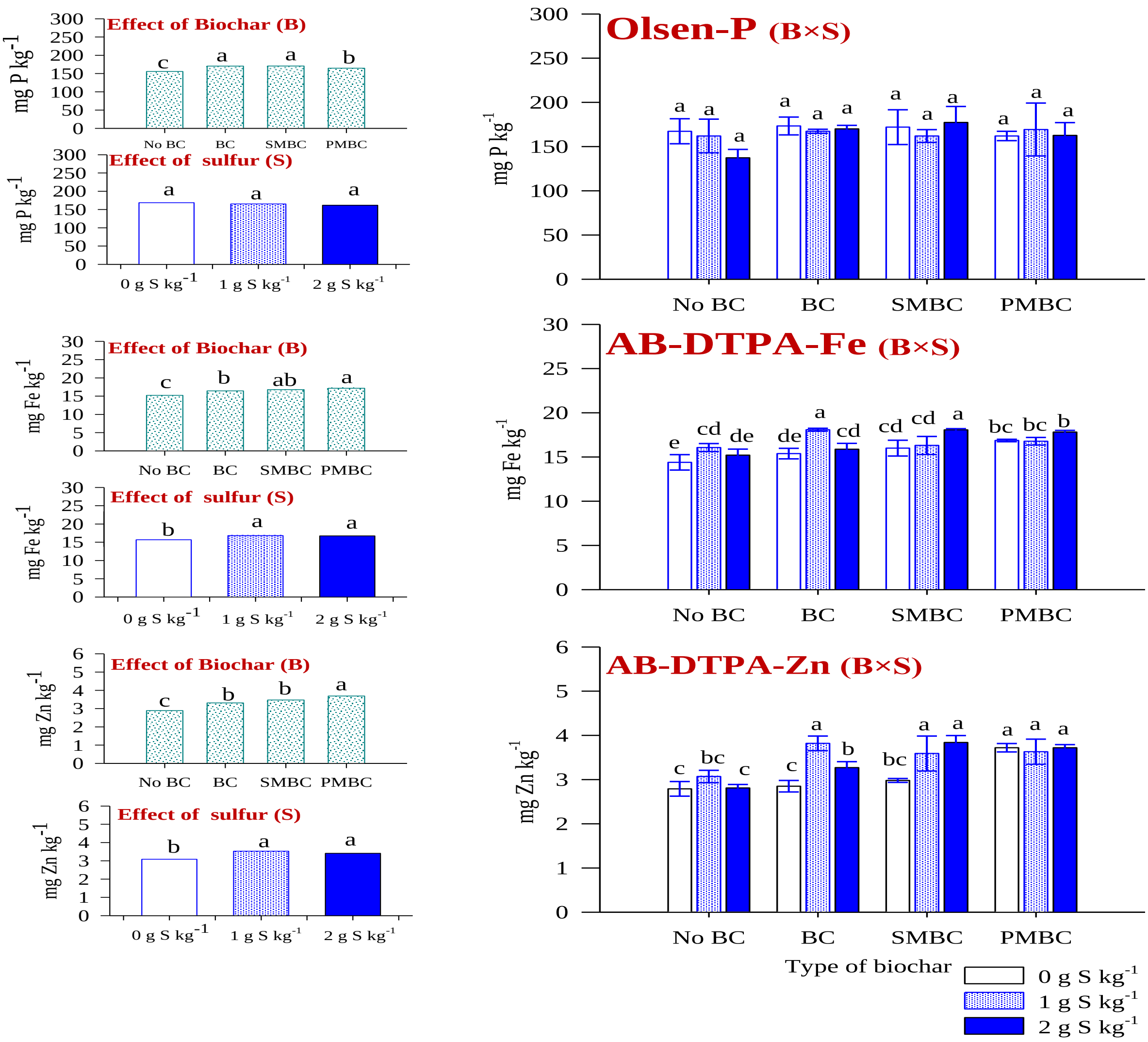

Fig. 3. Effect of different types of biochars and S application doses on available contents of P (P-Olsen), Fe (AB-DTPA-Fe) and Zn (AB-DTPA-Zn) in soil (means± standard deviations). No BC: no applied BC, BC: non-acidified biochar, SMBC: sulfuric acid modified biochar, PMBC: phosphoric acid modified biochar

Application of S raised both AB-DTPA-Fe and AB-DTPA-Zn concentrations in soil, while recorded no significant impacts on Olsen-P. Interactions impacts of both biochar and elemental S were insignificant on Olsen-P, while noting significance on both AB-DTPA-Fe and AB-DTPA-Zn. For example, the least values of both AB-DTPA-Fe and AB-DTPA-Zn were found in the control treatment that did not receive any additive, while the highest AB-DTPA-Fe was found in each of "BC+1 g S kg^{-1}" and SMBC+2g S kg^{-1}", with no significant variations between them. In case of AB-DTPA-Zn, its concentrations were the highest in soils amended with acid modified biochars as well as the one that received "BC+1 g S kg^{-1}".

3.4. Effect on the carbon balance

Application of all types of biochar did not significantly affect C content in plant tissues (Fig 4). Also, S additions did not significantly influence this content. Thus, sequestered C in plant tissues was calculated as a multiplication function of plant dry weights × C content within plant tissues then the carbon cycle feedback was evaluated according to Farid *et al*. (2022) as the difference between C-outputs “summation of sequestered C in plant tissues and residual organic carbon in soil” minus C-inputs “the summation of soil organic C (prior to cultivation) and applied carbon via biochars and compost”. Concerning the calculations of C balance in soil (CBS_W), results obtained herein (Fig 4) indicate that all the calculated values of CBS_W were positive ones. Other calculations were conducted after excluding carbon sequester in roots (CBS_A) because plant roots that are always kept under ground and straightforward undergo degradation. In this context, the CBS_A values, based on the aboveground maize parts only, were positive only in the soil that was not amended with either biochar or S, as well as the ones received PMBC(-S), BC+4 g S kg^{-1} and SMBC+2 g S kg^{-1}.

3.5. Plant growth parameters in relation with soil characteristics and nutrient availability

Table 3 reveals that maize dry weights as well as plant stem diameters was correlated significantly and negatively with soil pH. This parameter (pH) was also correlated significantly and positively with AB-DTPA extractable concentrations of both Fe and Zn, but not with Olsen-P. Further factors might affect Olsen-P rather than soil pH. It is worth noting that maize dry weights were correlated significantly and positively with each of Olsen-P and AB-DTPA Zn (not with AB-DTPA-Fe) and that the extractable contents of AB-DTPA Fe and AB-DTPA Zn affected significantly and positively the stem diameter. Moreover, the plant height was correlated significantly with AB-DTPA Zn content in soil. On the other hand, plant heights were not significantly correlated with soil pH. Likewise, neither of soil EC nor residual soil organic carbon (ROC) were correlated significantly with any of the investigate growth parameters. Nevertheless, stem diameter and plant height were correlated significantly with the carbon content in plants.

Table 3. Coefficient of determination (r^2) values calculated for the relations among plant growth parameters, nutrient available contents in soil and its characteristics

	Plant dry weight	Plant height	Stem diameter	Olsen-P	AB-DTPA-Fe	AB-DTPA-Zn	pH	EC	ROC	C-content in plant
Plant dry weight		0.285	**0.508****	**0.335***	0.219	**0.356***	**-0.521****	0.021	0.011	-0.107
Plant height			**0.573****	0.171	0.281	**0.357***	-0.308	-0.040	0.084	**-0.462****
Stem diameter				0.141	**0.433****	**0.513****	**-0.400***	0.148	0.284	**-0.440****
Olsen-P					0.215	0.136	0.101	-0.145	0.110	-0.074
AB-DTPA-Fe						**0.875****	**-0.394***	0.251	0.063	-0.225
AB-DTPA-Zn							**-0.516****	0.159	0.240	-0.286
pH								-0.232	0.126	0.038
EC									0.125	0.154
ROC										-0.270
C-content in plant										

EC: electric conductivity, ROC: residual organic carbon

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

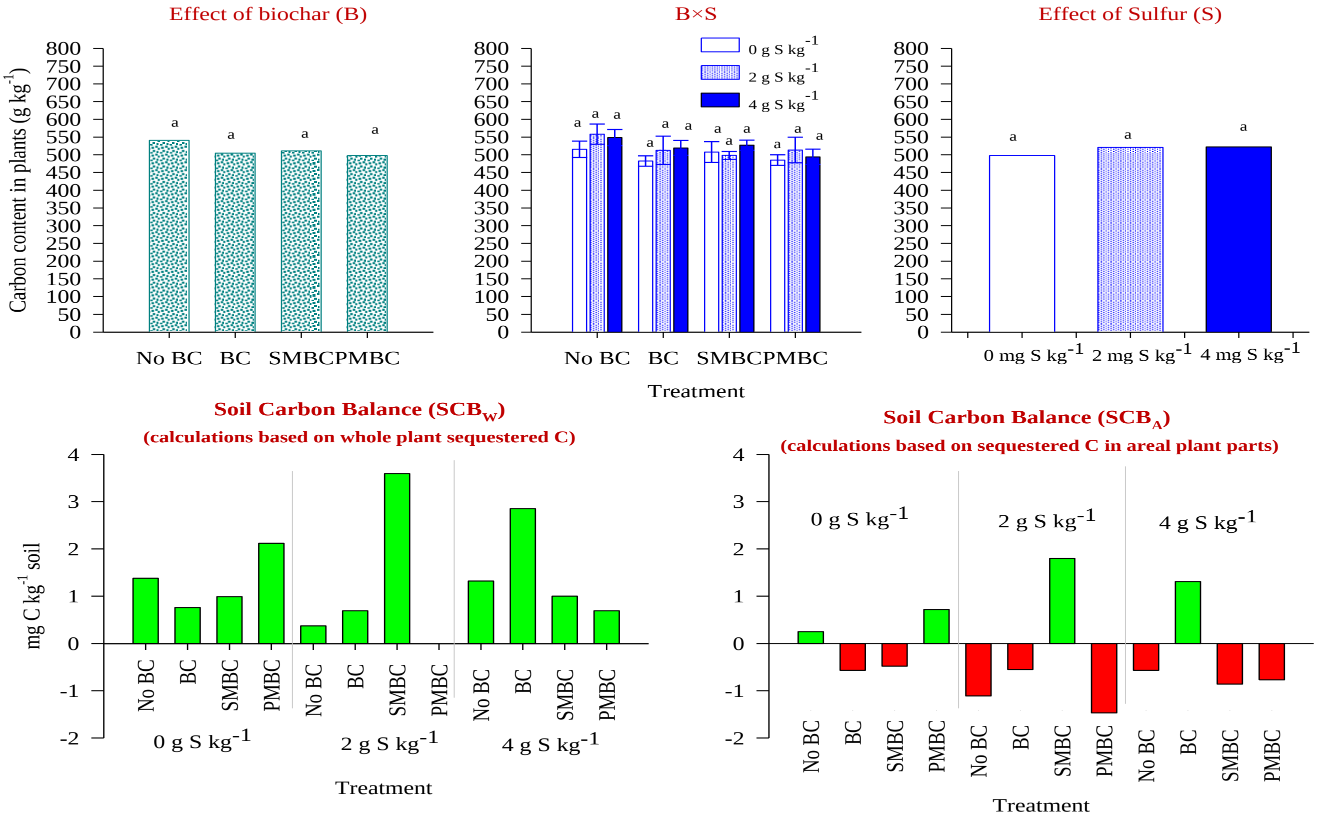

Fig. 4. Effect of different types of biochars and S applications at different rates on the carbon content within different plant parts and the carbon balance in soil (mean± standard deviation). No BC: no applied BC, BC: non-acidified biochar, SMBC: sulfuric acid modified biochar (Sulfurized biochar), PMBC: phosphoric acid modified biochar Similar letters indicate no significant variations among treatments.

4. Discussion

4.1. Vegetative growth parameters of maize plant as affected by application of both biochar and elemental sulfur

Plant dry weights and maize heights increased significantly owing to application of acidified biochar i.e. SMBC and PMBC; yet the corresponding increases owing to application of the non-acidifed biochar were insignificant. This is probably because the non-acidified biochar raised soil pH (Dai *et al.*, 2017; Zhang *et al.*, 2019; Shetty and Prakash, 2020) and this may temporarily diminish nutrient availability in soil (Rashid *et al.*, 2020). On the contrary, acidified biochars improved soil characteristics and upgraded soil fertility (Ippolito *et al.*, 2016; Saifullah *et al.*, 2018) and this in turn enhanced plant growth (Abd El-Mageed *et al.*, 2021). The positive effects of biochar were noted on growth of tomato (Tripti *et al.*, 2017), spinach (Jabborova *et al.*, 2021), wheat (Lalarukh *et al.*, 2022) and squash (Tolba *et al.*, 2021; Farid *et al.*, 2022), on the other hand Schmidt *et al.* (2014) did not observe significant increases in grapes owing to biochar applications. These results validate the first hypothesis. Application of S at its different rates i.e. 0, 1 and 2 g S kg^{-1} recorded no further significant impacts on either plant dry weight, plant height or stem diameter. The above results; therefore, did not support the second hypothesis as acid modified biochars were still more efficient in improving plant growth versus the usage of non-acidified biochar+ elemental S.

4.2. Soil chemical characteristics as affected by application of both biochar and elemental sulfur

- Soil pH: Application of the non-acidified biochar (BC) raised significantly soil pH versus the control, and this may be because of the alkaline nature of biochar (Dai *et al.*, 2017; Elshony *et al.*, 2019). In contrast, acidified biochars (SMBC and PMBC) decreased significantly soil alkalinity with no significant variations in soil pH detected between these two amendments and; therefore these results justify the third hypothesis. Application of S also decreased significantly soil pH. Such reductions were more pronounced with increasing the dose of applied

S from 2 to 4 g S kg^{-1}. Probably, S underwent biochemical oxidation in soil forming sulfuric acid and, this consequently released proton that decreased soil pH (Zheng *et al.*, 2019).

- Soil EC: SMBC application raised significantly soil EC while BC recorded no further significant effect on soil salinity versus the control. Maybe, more soluble salts were set free from biochars upon their degradation (Karimi *et al.*, 2020); yet some of these salts become insoluble under the alkaline conditions caused by BC application. In case of PMBC, it is thought that H_3PO_4 modification break the functional groups of this amendment forming disordered carbon structure of high sorption capacity and high CEC (Zeng *et al.*, 2022). This may increase considerably sorption of soluble salts versus the control as found by Wand *et al.* (2022) thus decreased soil EC. Accordingly, the fourth hypothesis becomes valid.Application of elemental S also upraised soil EC, especially with increasing the dose of application. This is because S underwent oxidation in soil, thus increased the solubility of soil nutrients (Pourbabaee *et al.*, 2020), beside of the formation of soluble ion pairs with other nutrients (Nasser *et al.*, 2020); accordingly soil EC increased with S applications.

- Residual organic carbon (ROC): All applied biochars significantly elevated ROC content in soil. Many results confirm this finding (Abdelhafez *et al.*, 2014; Bassouny and Abbas, 2019; Abdelhafez *et al.*, 2021; Farid *et al.*, 2022). The increases in ROC followed the sequence of BC≈PMBC>SMBC. May be SMBC exhibited high degradation rate in soil comparable with other biochars, thus its ROS seemed to be significantly low (Zhao *et al.*, 2017). According, these results endorse the fifth hypothesis. On the other hand, there was no further significant effect for the application dose of S on the residual soil organic carbon.

4.3. NPK uptake by maize plants as affected by application of both biochar and elemental sulfur

All applied biochars raised significantly extractable amounts of P, Fe and Zn in the studied soil by the end of the experimental trial. Such increases were almost the consequences of biochar degradation in soil. Regarding Olsen-P, the highest increases were attained for the application of either BC or SMBC. On the other hand, the highest increases in AB- DTPA extractable contents of Fe and Zn were accomplished by PMBC application while the results of the other two biochars seemed to be comparable. Maybe, P availability increased initially with using PMBC and this amendment, on the other hand, increased the availability of micro-nutrient (Souri and Sayadi, 2021) which in turn formed less soluble salts with P (Kootstra *et al.*, 2019). On the other hand, application of elemental sulfur did not significantly affect P available content in soil, while raised the extractable AB-DTPA contents of both Fe and Zn. Such increases in micro-nutrient concentrations could form immobile salts with P. This might explain why P uptake by Saskatoon berry decreased owing to excessive additions of elemental sulfur in alkaline soil according to Sun *et al*. (2022).

4.4. Soil carbon balance as affected by application of both biochar and elemental sulfur

Concerning the calculations of C balance in soil (CBS_W), all the calculated values of CBS were positive and this indicates that the sequestered C was probably higher than its emission losses from soils for all treatments. This result confirms the 6th hypothesis. In this context, the CBS_A values, based on the aboveground maize parts only, were positive in soil not amended with either biochar or S, while changed into negative values in soil non-amended with biochar while received the elemental S at either 2 or 4 g $kg^{-1.}$ Maybe, elemental sulfur increased the availability of nutrients (Sunil *et al.*, 2022) that were utilized by soil biota (Adomako *et al.*, 2021; Orwin *et al.*, 2021); hence increased the degradation speed of applied organic matter (Malik *et al.*, 2021).

Biochar applications significantly raised C-losses in the investigated sandy soil; therefore almost all values of CDB_A were negative. This is because the adjacent sand particles exhibit relative low specific heat capacity (Abu-Hamdeh, 2003); hence these particles gain heat fast and worm up. This consequently speeds up the rate of organic matter degradation (Conant *et al.*, 2011), even for the relative stable organic amendments known as biochars (Bassouny and Abbas, 2019). A point to note is that biochar application could increase substantially the degradation of soil organic matter (Sánchez-García *et al.*, 2015)

Generally, efficient photosynthesis process exhibited higher sequestered C and consequently better plant growth (Kim *et al.*, 2007). This process was mostly enhanced by the usage of efficient soil additives such as biochar (Farid *et al.*, 2022). In the soil amended with non-acidified biochar, the only positive CBS_A value was recorded for the soil that received the highest application rate of S. Maybe, S increased nutrient availability in soil to be utilized by soil biota. This biota built up its own organic matter (microbial bio-products) which is more resistant than the applied one (Abdelhafez *et al.*, 2018). Thus, S application was found to increase slightly residual organic carbon in organics-amended soil (Lisowska *et al.*, 2022). In case of acidified biochar SMBC, only 2 g S kg^{-1} were acceptable to attain a positive CBS value.

5. Conclusion and Future Prospective

Acidified biochars (SMBC and PMBC) were more preferable as soil amendments for improving the characters of the poor fertile light textured soil and enhancing plants grown thereon than the non-acidified one (BC). These acidified biochars decreased soil pH; and this in turn increased micronutrient availability in soil; that enhanced plant growth. On the other hand, normal biochar raised soil pH which was correlated negatively with AB-DTPA-Fe and Zn and also with plant dry weights. Although, the interactions between non-acidifed biochar and S recorded further positive impacts on nutrient availability and plant growth, especially at the highest application rate of S versus using each amendment solely; yet such increases were still below the ones recorded for acidified biochars. Future perspectives are needed to investigate the efficiencies of using these additives under field conditions for at least two successive seasons while evaluating the economic and environmental outcomes for these additives.

List of abbreviations:

BC: non-acidified biochar

SMBC: sulfuric acid modified biochar (Sulfurized biochar)

PMBC: phosphoric acid modified biochar

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

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