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Increasing Maize Productivity in Arid Sandy Soils using Combinations of (Normal/Acidified) Biochar and Elemental S

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SUSTAINABLE food production is the main challenge in today's world. Around one third of the food consumption worldwide is wasted; instead, these litters could be pyrolyzed forming biochar that can be applied to restore soil fertility. Yet, both the Egyptian soils and biochar are basic. The current study aims at investigating to what extent "elemental-S+ biochar" and "sulfuric-acid-modified biochar (SMBC)" can improve the nutritional status of maize plants and boost their growth performance under the arid conditions versus normal biochar. A non-amended control treatment was included for data comparison. Acidified and non-acidified biochars were produced from potato-straw then incorporated in a pot experiment, considering two factors: (1) acidified and non-acidified biochars (**all** applied at 10g kg^{-1} soil) and (3) elemental-sulfur applied at three rates: 0, 1 and 2 g S kg^{-1}. All pots received compost as a source of nutrients Maize seeds were then planted in all pots for 60 days. The dry-weights of maize roots and shoots improved significantly for only SAMB treatment because this treatment decreased soil pH, consequently increased the availability of Olsen-P, S, and AB-DTPA-Zn, while reduced AB-DTPA-Fe and K-available content. Nevertheless, all biochars increased nutrient uptake by plants, with superiority for SMBC. Moreover, SMBC stimulated the transfer of K, Fe and Zn from root-to-shoot. Likewise, S-applications decreased soil pH. This, in turn, increased AB-DTPA extractable- amounts of Fe and Zn when being applied at the lower dose; yet exhibited no effect on Olsen-P and K availability. Its main mechanism was via increasing nutrient uptake by plants which boosted shoots and roots biomasses. Overall, the increases in plant biomasses were significantly correlated with increasing nutrient uptake by plants. Results also revealed that SMBC exhibited better shoot growth and higher chlorophyll content than the dual application of "non-acidified biochar+S". In spite of that, the latter treatment exhibited higher contents of K and Zn (but not Fe) in shoots. In conclusion, application of elemental S can increase the efficiency of applied biochar to increase soil productivity; in spite of that, acidified biochar is more preferable as a fertilizer in arid soils.

Keywords: Elemental sulfur, maize; sulfuric-acid-modified-biochar; sandy soils; nutrient uptake.

1. Introduction

Sustainability in food production is the main challenge of today's world (Malik *et al.*, 2022) because of the continuous population growth worldwide, especially in developing countries (van Hoof *et al.*, 2019). Around one third of the food consumption is wasted and this brings further economic costs (Morone *et al.*, 2019). Instead, organic wastes should be quantified and recycled appropriately (Ojha *et al.*, 2020). For example, farm residues may undergo pyrolysis in absence of oxygen or under limited oxygen conditions (Bassouny and Abbas, 2019; Tolba *et al.*, 2021; Farid *et al.*, 2022) forming a black product rich in carbon called the black diamond (Abdelhafez *et al.*, 2017). This cost-effective product is rich in nutrients (Elshony *et al.*, 2019) which can promote nutrient absorption by plants (Hou *et al.*, 2022); hence enhance plant growth performance (Hou *et al.*, 2022) and productivity (Chew *et al.*, 2022). In the future, this additive (biochar) may substitute totally chemical fertilizers (Hou *et al.*, 2022).

Many reports confirmed the positive impacts of biochar application on soil characteristics (Devereux *et al.*, 2012; Burrell *et al.*, 2016) which are mainly attributed to its high surface area, porosity, and surface charges (Hossain *et al.*, 2020; Asaad *et al.*, 2022). It persists longer in soil versus other organic additives such as compost (Farid *et al.*, 2022) and therefore restore soil health via stimulating beneficial microorganisms (Agarwal *et al.*,

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2022; Haider *et al.*, 2022). This consequently support plant growth and development (Agarwal *et al.*, 2022; Ma *et al.*, 2022; Hegab *et al*., 2024). In particular, biochar can successfully be used for boosting maize productivity (Bassouny and Abbas, 2019; Sun *et al.*, 2022).

Maize is an important cereal crop in Egypt (Abdelraof *et al*., 2023), coming after wheat and rice (Ali and Abdelaal, 2020). It is incorporated in manufacturing of up to 70% of the dry feed (Mekawy and Gmail, 2022). Nevertheless, the majority of it local consumption in Egypt depends on exports (Eliw *et al.*, 2022). Since the beginning of the Russia-Ukraine War, maize prices have increased by 35% (Ben Hassen and El Bilali, 2022). Thus, there is an actual need to increase its local production.

The majority of newly reclaimed areas that can be used for maize cropping in Egypt are sandy textured ones of low organic matter and nutrient contents (El-Nagar and Sary, 2021). These soils also exhibit low capabilities to retain nutrients within the top soil (Niel, 2021). Maybe, the application of biochar improves nutrient retention capacity in such soils (Hossain *et al.*, 2020; Farid *et al.*, 2021); yet Egyptian soils are mainly basic (Abd El-Mageed *et al.*, 2021). Thus, sole application of biochars may; therefore, have undesirable effects on the agricultural productivity. Its alkaline nature (Chen *et al.*, 2019; Kocsis *et al.*, 2022); could rise the pH of soil and minimize nutrient availability (Hossain *et al.*, 2020). Alternatively, application of acidified biochar (Abd El-Mageed *et al.*, 2021) or using an acidifying agents such as elemental sulfur + biochar may further enhance plant growth (Bashir *et al.*, 2020).

Modifying biochar with acids may additionally increase its specific surface area (Murtaza *et al.*, 2022), especially its content of oxygen-containing-functional groups such as the carboxyl ones (Huang *et al.*, 2021) to retain more soil nutrients (Asaad *et al.*, 2022). This is a good point deemed to improve the characteristics of these soils. Nevertheless, acid modified biochar becomes easily biodegradable in soil versus non acidified biochars (El-Sharkawy *et al.*, 2022; Abuzaid et al., 2025); therefore, more nutrients are thought to be released during its decomposition which in turn are subjected to be lost via leaching. Otherwise, the usage of elemental sulfur may undergo oxidation in soil; hence decrease soil pH (Mattiello *et al.*, 2017), while increase the pH dependent charge (Choppala *et al.*, 2018) of the organic functional groups to adsorb and retain more soil nutrients (Fidel *et al.*, 2018). There is a lack of experimental evidence to confirm the integral effect of elemental sulfur and biochar for boosting productivity of crops within the arid poor fertile soils.

The current study aims at investigating to what extent can biochar+sulphur (relatively cheap additives) improve the nutritional status of maize plants and boost their growth performance under arid conditions versus application of either biochar or even the modified biochar with sulfuric acid (a rather expensive additive). This aim was intended to be conducted under greenhouse conditions to monitor precisely variations in nutrient availability, specifically P, K, Fe and Zn, their distribution within plant parts and outcomes on plant growth and productivity. This goal is not so far investigated. Specifically, we anticipate that sulfuric acid modified biochar could effectively increase nutrient uptake by plants and this in turn increase plant growth and productivity versus application of non-acidified biochar **(hypothesis 1)**. Also, application of elemental sulfur could ameliorate the negative effects of biochar application on enhancing plant growth and productivity **(hypothesis 2)**. The effects of the relatively low cost additives (biochar+ elemental sulfur) on plant nutritional status and growth performance could be competent or even superior to the effect of the relatively expensive sulfuric acid modified biochar **(hypothesis 3)**.

This study contributes to increase food security via enhancing the productivity of maize in dry, nutrient-deficient soils through sustainable soil improvement methods,. Thus, this research is closely connected to the United Nations Sustainable Development Goals (SDGs), specifically focusing on SDG 2 (Zero Hunger) and SDG 15 (Life on Land). Furthermore, the incorporation of biochar derived from organic waste addresses SDG 12 (Responsible Consumption and Production) by converting agricultural waste into a valuable soil supplement, thereby decreasing wastes and promoting the circular use of resources. The use of eco-friendly materials and techniques, like biochar and elemental sulfur, to restore soil fertility also supports efforts for ecological conservation in line with SDG 13 (Climate Action) by improving soil carbon storage and reducing dependence on chemical fertilizers.

2. Materials and methods

2.1. Materials of study

Compost was brought from the Compost Production Unit at Faculty of Agriculture (**Benha University**). Its characteristics are presented in supplementary Table 1. A top 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, crashed and sieved via 2 mm sieve then analyzed for its physicochemical characteristics as outlined by Klute (1986) and Sparks et al. (2020). This soil was of loamy sand texture (87.7 % sand, 6.5% silt and 5.8% clay) comprising 6.0

g kg^{-1} organic matter and 29.9 g kg^{-1} calcium carbonate. Its salinity is 3.33 dS m^{-1} and the pH was 8.4. Its water holding capacity was 26.6%. Maize seeds of cultivar SC-P3444 were obtained from Pioneer International Company in Egypt.

2.2. Preparation of the acidified and non-acidified biochars

Potato straw was collected from the experimental farm at Faculty of Agriculture, Benha University. These residues underwent pyrolysis at 450˚ C in a muffle furnace (VULCAN D-550) for 5 h to produce biochar; thereafter the product was ground to pass through a 0.18 mm sieve. Half of the pysolyzed product was left untreated **(BC)** while the other half was mixed with sulfuric acid to produce **sulfuric acid modified biochar (SMBC)** as outlined by Vithanage *et al.* (2015). Briefly, sulfuric acid (30%) was mixed with biochar at a ratio of 20:1 for 4 h, then washed with distilled water 5 times and oven dried at 40°C.

2.3. The green house investigation

A pot experiment, followed a randomized complete block design, was conducted at the greenhouse conditions of Soils and Water Department at Faculty of Agriculture, Moshtohor, Benha university, Qalyoubia Governorate (Egypt). This experiment comprised two factors, the first one was the type of biochar **(**no biochar, non-acidified biochar (BR) and sulfuric acid modified biochar (SMBC) (all biochar additives were applied at a rate of 10g kg^{-1}) while the second factor was elemental sulfur which was applied at three different doses (0, 1 and 2 g kg^{-1}). All treatments were replicated three times.

To set up this experiment, plastic pots (20cm diameter ×17.5cm depth) were washed several times with tap water then with distilled water and uniformly packed with soil (equivalent to 5 kg soil mixed with one of the abovementioned amendments + 80 g of compost as a source of beneficial biota and nutrients). Soils were then moistened (with distilled water) to bring soil moisture at 80% of water holding capacity and left to equilibrate for two weeks while maintaining soil moisture gravimetrically at this moisture level. Afterward, 5 maize seeds were planted per pot, and after germination, plants were thinned to 3 plants. Soil moisture was kept at 80%of the water holding capacity for 60 days (experimental period), then whole plants were removed gently from pots to avoid the damage of root hairs and placed on plastic sieves.

Plant materials were washed thoroughly with tap water then with distilled water and oven dried for 72h at 60-70˚ C thereafter weights of the dried materials were determined. Moreover, soil samples were collected from the rhizosphere of each pot and air dried for available nutrient analyses.

2.4. Soil and plant analyses

Soil pH was determined in 1:2.5 soil water suspension using a pH meter (Jenco 6173), Available K was extracted by ammonium acetate method according to Sparks et al. (2020) then measured by flame photometer (Elico CL 378). Available P was extracted by Olsen then determined by Spectrophotyometer (Spectronic 20D) following the molybdenum blue-ascorbic acid method 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).

Chlorophyll content in maize shoots was determined by Chlorophyll Content meter (Opti-Sciences CCM-200) the day before plant harvest (59 days after seedling). The oven dried plant materials were wet digested using a mixture of sulfuric (H_2SO_4) and perchloric ($HClO_4$) acids at a rate of 4:1, according to Gotteni *et al.* (1982). K and P contents in plant digests were measured via flame photometer and Spectrophotometer, respectively. Fe and Zn were determined by Atomic absorption. All the chemicals, used in this study, were of analytical grade.

Data processing

The obtained data were subjected to two- way ANOVA and Dunken’s text via SPSS ver 18. Figures were plotted via Sigma plot 10.

3. Results

3.1. Effect of biochars and S on plant dry weights

Dry weights of maize shoots and not roots increased significantly owing to amending the investigated sandy soil with acidified biochar (SMBC) (Fig 1). In contrast, the non-acidified biochar recorded no significant increases in shoot biomass while decreased root biomass. Likewise, application of S boosted root and shoot dry weights; yet such increases were only significant with the application of 2 g S kg^{-1}.

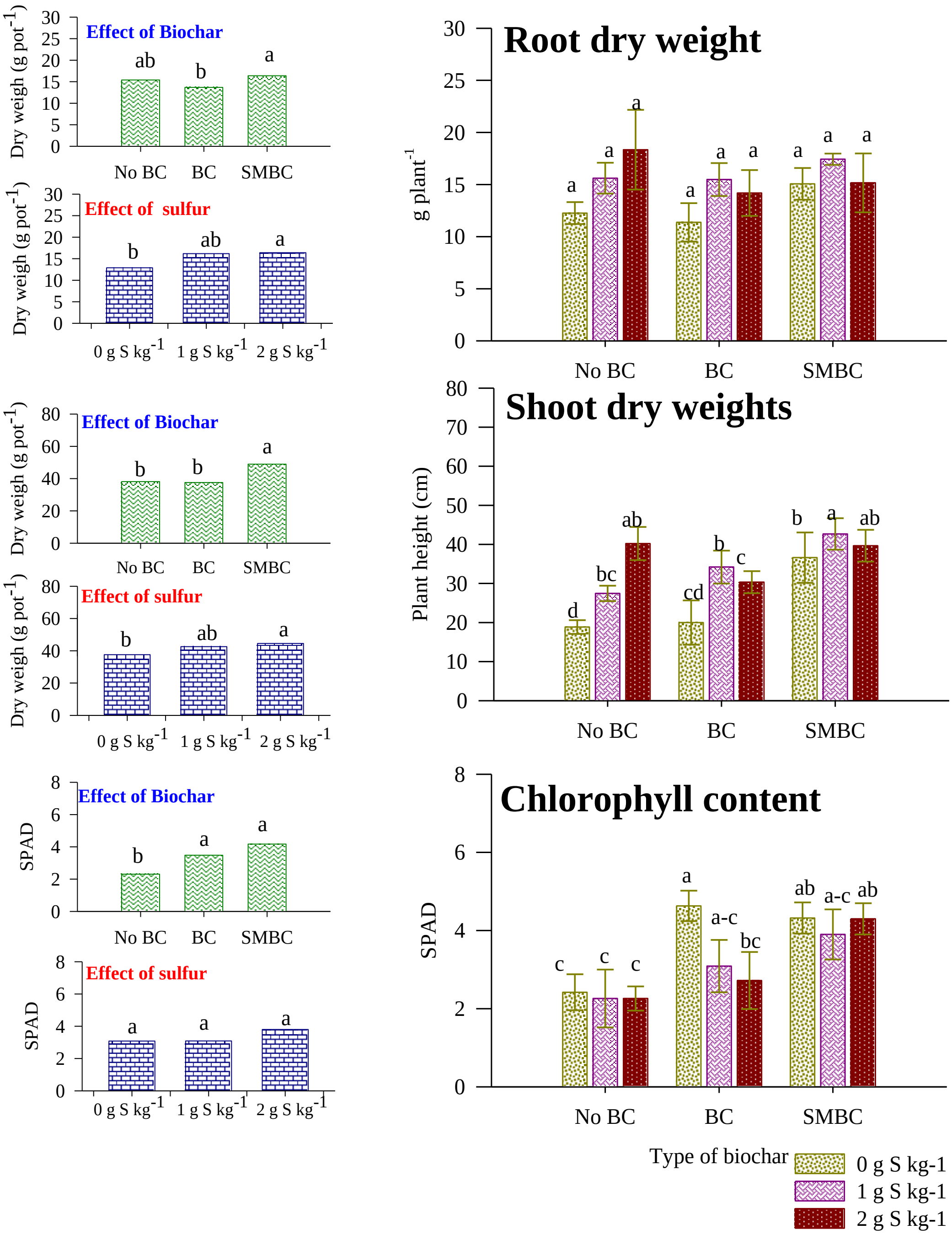

Fig. 1. Effect of biochars and S applications at different doses on plant chlorophyll content. Abbreviations: BC: Non-acidified biochar, SMBC: Sulfuric acid modified biochar. Similar letters indicate no significant variations among treatments.

Concerning interactions between biochar and elemental-S, the highest increases were recorded for SMBC, irrespective of the rate of S application (1 or 2 g kg^{-1} soil). Also, treatment that did not receive biochar while received 2 g S kg^{-1} recorded comparable increases in shoot dry weights. On the other hand, no significant interactions were recorded for the application of both biochar anf S on root dry weights.

3.2. ***Effect of biochars and S on plant Chlorophyll***

Chlorophyll content also augmented significantly in plant shoots grown on the soil amended with either the acidified or non-acidified biochars, yet the variations between these two treatments were almost insignificant (Fig. 1). It was noticed that chlorophyll content was almost doubled in plants which were amended with SMBC versus the control. On the other hand, S applications did not exhibit significant effects on the chlorophyll content in plants. Probably, the impacts of biochar addition on this parameter were more obvious versus those of elemental S. Interactions between biochar applications and S reveals that all biochar applications (-/+ S) exhibited comparable chlorophyll content to the control, except for “BC+0 g S kg^{-1}”, “SMBC+0 g S kg^{-1}” and “SMBC+ 2 g S kg^{-1}” treatments, which recorded higher increases in chlorophyll content in maize shoots.

3.3. Effect of biochars and S on soil pH

Application of acidified biochar decreased significantly soil pH while the non-acidified biochar raised significantly soil pH to values exceeding those of the control (Fig 2). Also, S- applications decreased significantly soil pH, especially with increasing its dose of application i.e. 2 g S kg^{-1}. Regarding the interactions between these two factors (biochar and elemental S), it was found that the highest application rate of S in presence of either acidified or non-acidified biochars recorded the least pH values.

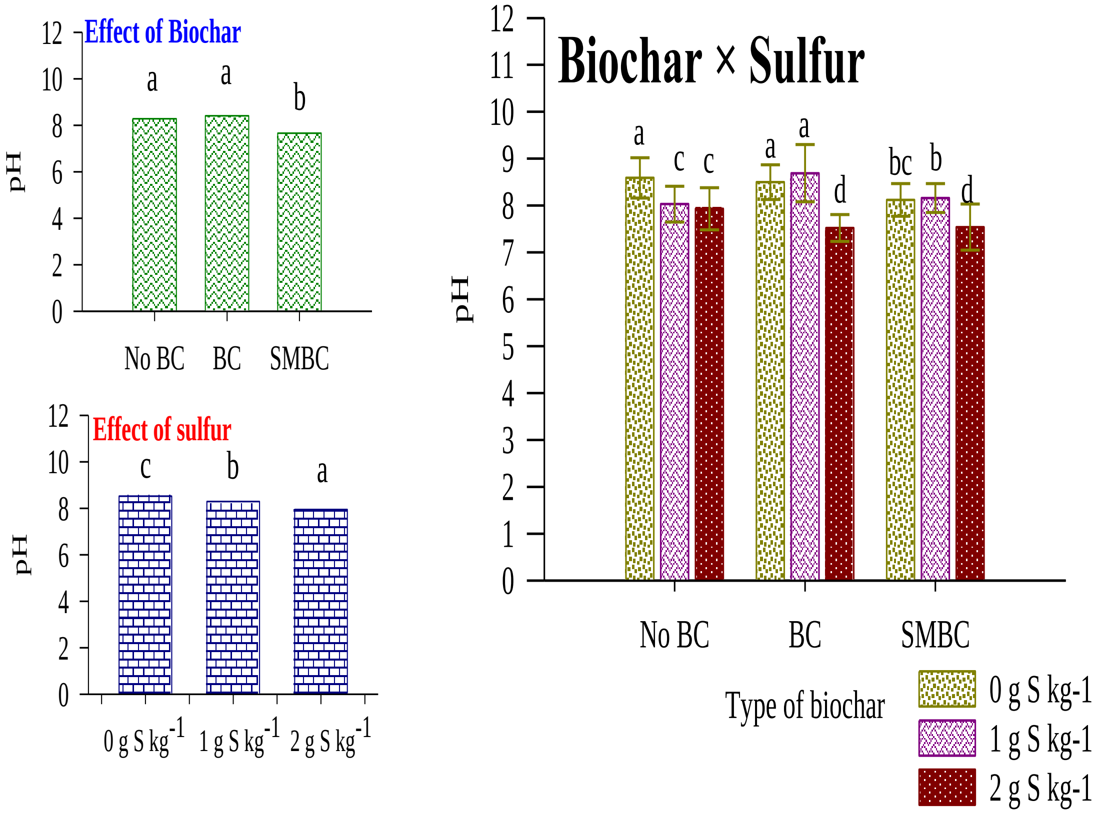

Fig. 2. Effect of biochars and S application rates on soil pH. See footnote Fig. 1. Similar letters indicate no significant variations among treatments.

.3.4. Effect of *biochars and S* on nutrients availability and concentrations within maize parts

3.4.1. Effect on K available content in soil and its concentration within plant roots and shoot

Application of non-acidified biochar significantly raised K-available content in the investigated soil by 1.8 fold, while the acidified biochar did not (Fig 3). Nevertheless, all applied biochars successfully upraised K- content in both shoots and roots, especially the non-acidified one. Likewise, application of elemental sulfur significantly elevated K content within maize shoots, especially with increasing the dose of applied S up to 2 g S kg^{-1} while the corresponding contents decreased in roots. Also, elemental S decreased K available content in soil. Concerning the interaction between S and biochar, K availability was the highest in all BC applications, irrespective of the rate of applied S.

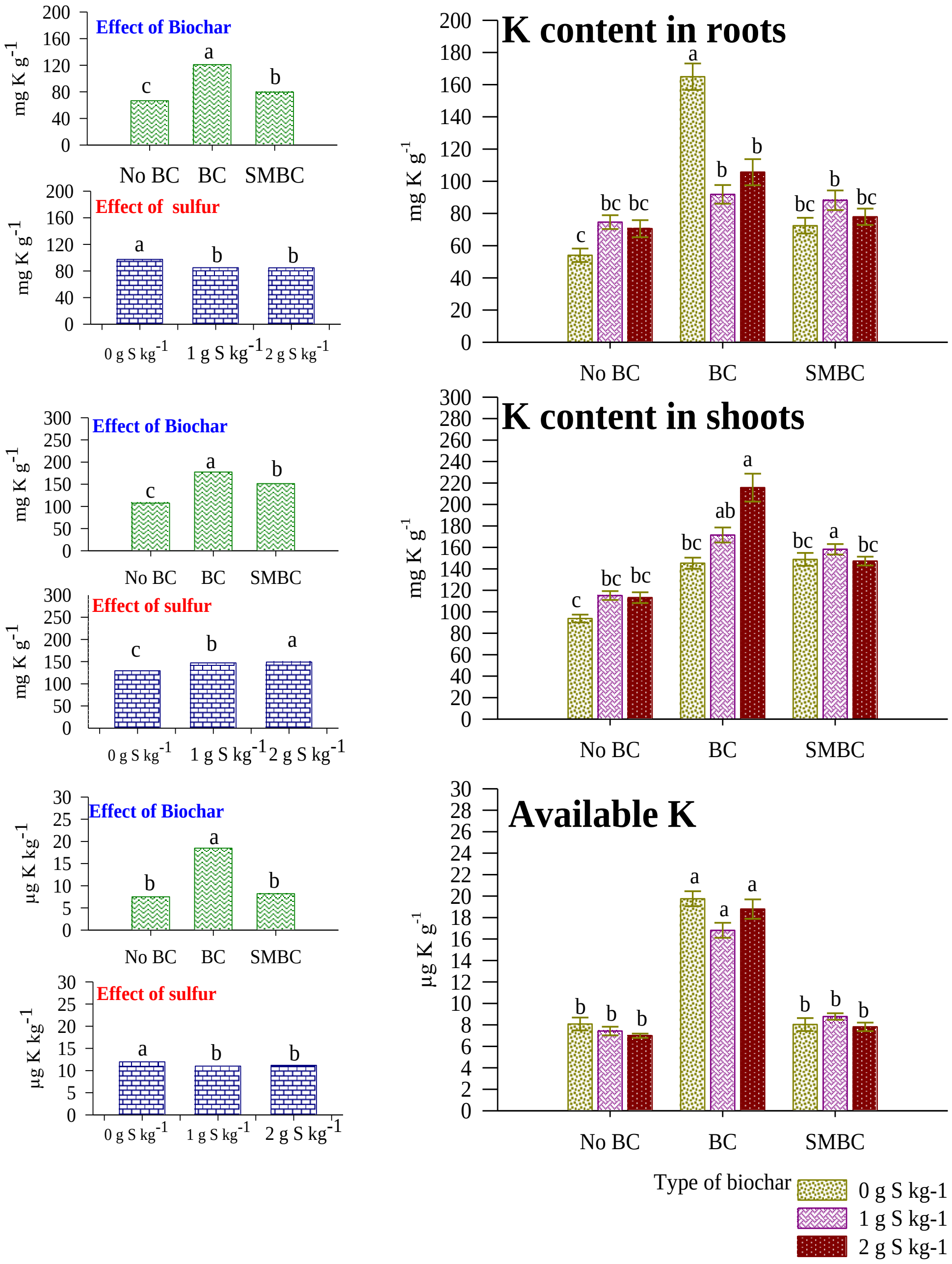

Fig. 3. Effect of biochars and S application rates on K available content in soil and its corresponding concentrations in both roots and shoots of maize plant. See footnote Fig 1. Similar letters indicate no significant variations among treatments.

The highest increases in K content in both roots and shoots of maize plants were also recorded for all BC treatments. A point to note is that the BC treatment, that did not receive S, recorded the highest K-content in roots, while the ones, that received S recorded the highest K contents in shoots. This might highlight the important role of S in translocation of K within plants.

3.4.2. Effect on P available content in soil and the corresponding concentrations in plant roots and shoots

Application of all biochars raised significantly P- concentrations within maize roots (2.8 fold for BC and 3.1 fold for SMBC) with no substantial variations between the non-acidified and acidified biochar treatments (Fig 4).

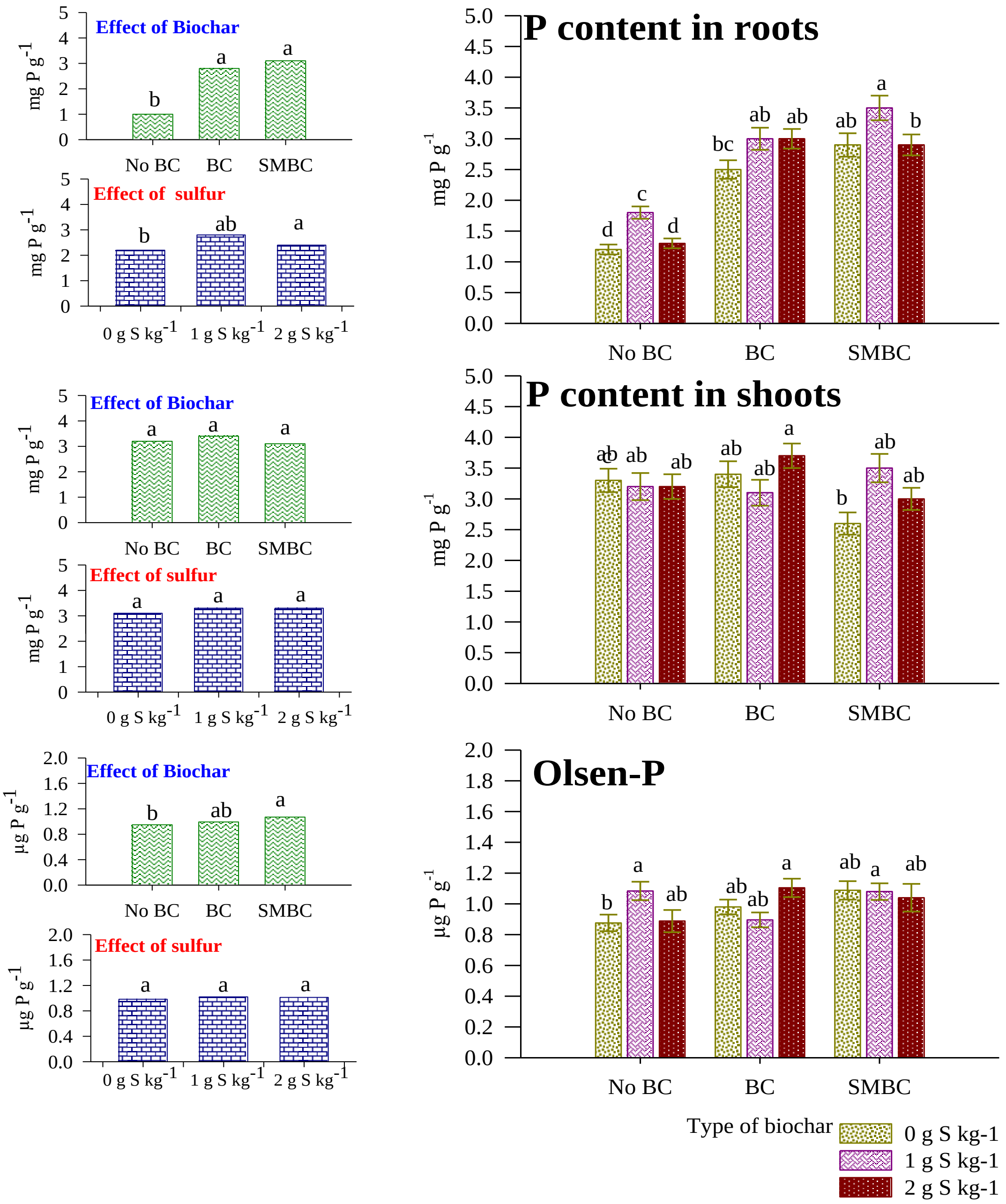

Fig. 4. Effect of biochars and S application rates on P-available content in soil and its corresponding concentrations in both roots and shoots of maize plant. See footnote Fig 1. Similar letters indicate no significant variations among treatments.

On the other hand, no significant variations were detected in P-content in shoots owing to biochars application. Concerning Olsen-P, only SMBC recorded significant increases in its content while the corresponding Olsen-P contents due to application of BC was significantly comparable to the control. Sulfur applications did not significantly affect the available P-content (Olsen-P) in soil by the end of the experimental period or even its concentration within different maize parts. Concerning interactions between biochar+ elemental-S, all treatments markedly increased P-Olsen versus the control, with no noticeable variations among these treatments. In maize roots, the highest increases were recorded for "SMBC+0 g S kg^{-1}", "SMBC+1 g S kg^{-1}", "BC+1 g S kg^{-1}" and "BC+2 g S kg^{-1}" treatments, while in shoots, values of P content were almost comparable except for SMBC treatment which exhibited a significantly lower value. Probably, such reduction was related to the dilution effect of this nutrient within plant tissues.

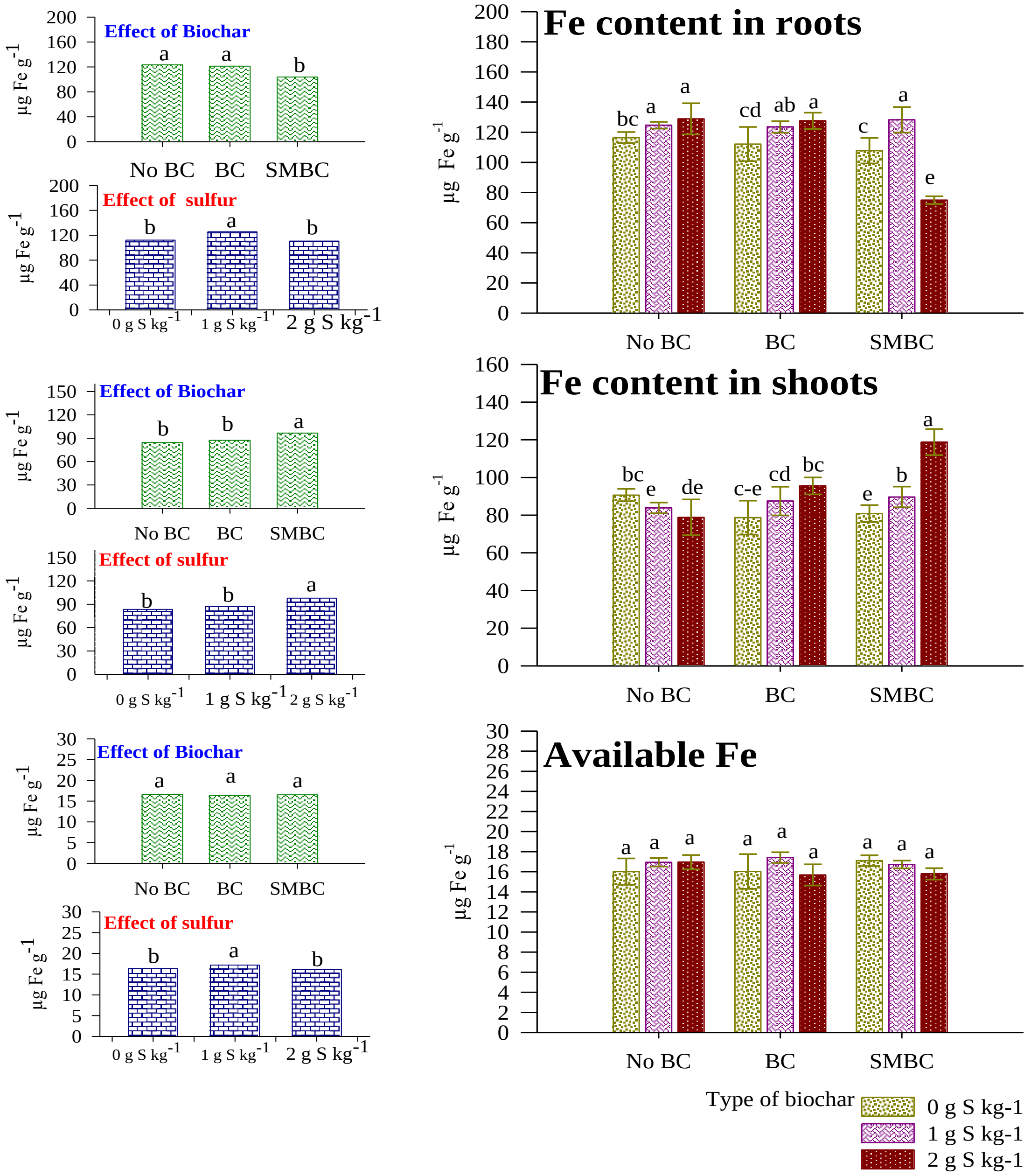

Fig. 5. Effect of biochars and S application rates on Fe-available content in soil and its corresponding concentrations in both roots and shoots of maize plant. See footnote Fig 1. Similar letters indicate no significant variations among treatments.

3.4.3. Effect on AB-DTPA- extractable Fe and concentrations of Fe within maize roots and shoots

Application of all biochars did not significantly affect AB-DTPA-extractable Fe in soil (Fig 5). Only the acidified biochar decreased Fe contents in roots by approximately 16% while raised this content in shoots by 1.14 folds. Application of elemental S also raised significantly AB-DTPA extractable-Fe content in soil at its low application dose i.e. 1 g kg^{-1}, and this consequently elevated its content in both roots and shoots. Nevertheless, Fe extractable amount in soil by AB-DTPA and the analogues content within maize roots decreased significantly with increasing the rate of S application to 2 g kg^{-1}, though these concentrations were still comparable with the control results. Remarkably, the highest Fe contents in shoots were recorded for plants that received 2 g S kg^{-1}. Generally, the interactions between biochar and S were insignificant regarding AB-DTPA extractable-Fe content in soil while exhibited significant variations in both roots and shoots. The highest Fe content was found in maize shoots due to application of SMBC+2g S kg^{-1}; nevertheless this treatment recorded the least Fe content in roots. Maybe, S stimulated Fe translocations to plant shoots.

3.4.4. Effect on AB-DTPA- extractable Zn and Zn concentrations within plant roots and shoots

Application of acidified biochar raised significantly AB-DTPA-extractable Zn in soil and also elevated Zn content in shoots by approximately 10%, while diminished its content in roots by 1.11 fold (Fig 6).

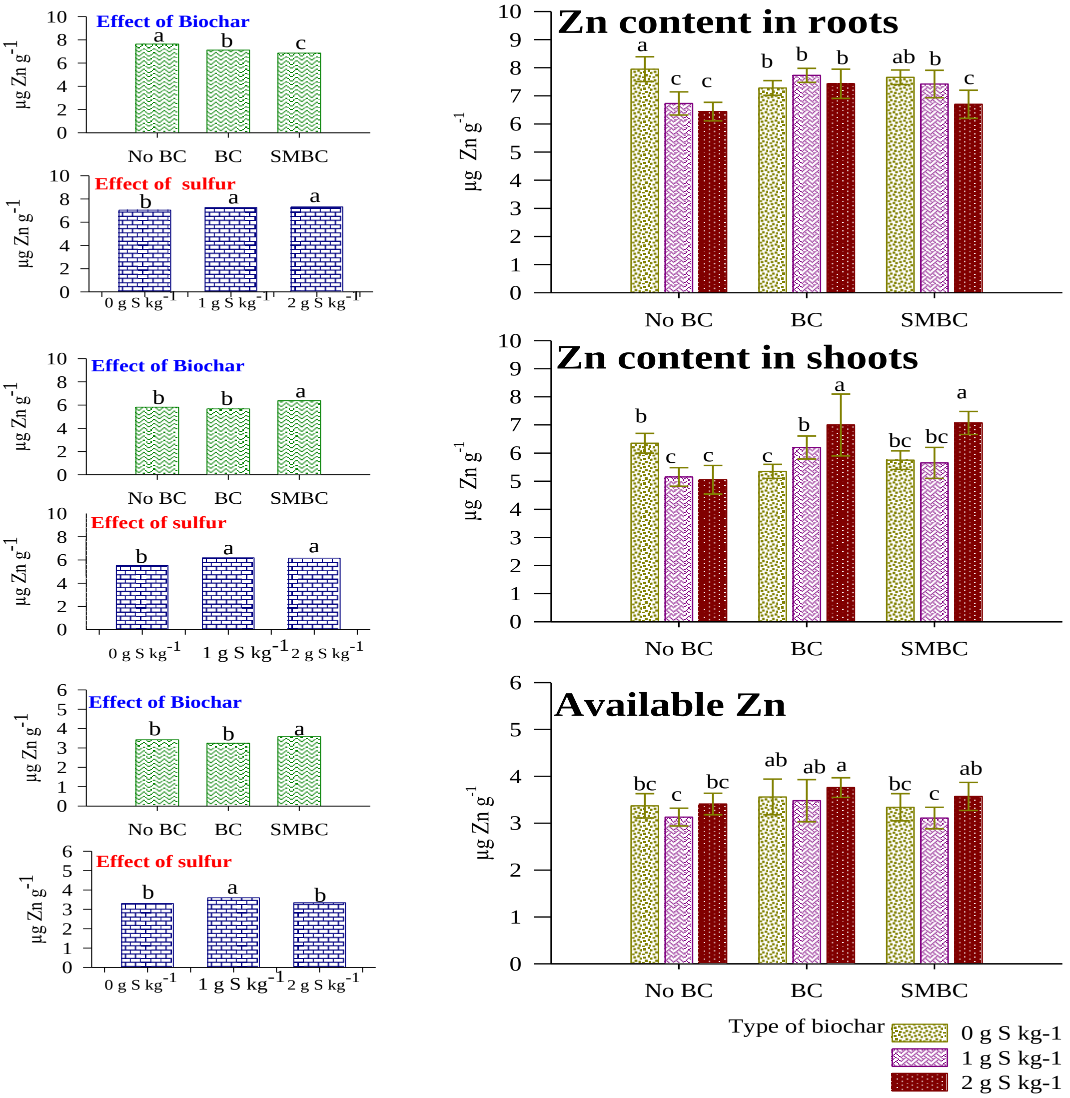

Fig. 6. Effect of biochars and S application rates on Zn-available content in soil and its corresponding concentrations in both roots and shoots of maize plant See footnote Fig 1. Similar letters indicate no significant variations among treatments.

Referring to the application of non-acidified biochar, this additive recorded no further significant impacts on the AB-DTPA extractable Zn versus the control. Also, this additive recorded comparable Zn content in shoots while decreased its content in roots. In case of elemental sulfur, its application raised significantly AB-DTPA-extractable Zn (at its lower application rate i.e. 1 g S kg^{-1}) and also upraised its content in maize roots and shoots. No further significant increases in Zn content within maize parts were noticed due to the application of higher S dose (2 g S kg^{-1}).

Interactions between biochar × S were of further significant effect on AB-DTPA-extractable-Zn and also on Zn content within both maize shoots and roots. The highest values of AB-DTPA extractable Zn were found in all “BC” treatments and also for the “SMBC+2 g kg^{-1}” one, with no significant variations among these treatments.

In maize shoots, the highest Zn content were recorded for “BC+2 g S kg^{-1}” and “SMBC+2 g kg^{-1}” treatments with no variations between these two treatments. On the other hand, these two treatments recorded significant lower Zn content within maize roots versus the non-amended “zero biochar+zero S” treatment

3.5. Correlations between root and shoot biomases in relation tp macro- and micro- nutrient uptake

Table 1 reveals that total dry weights of maize plants were significantly correlated with the uptake values of both macro- (K and P) and micro- nutrients (Fe and Zn) (uptake=Σ dry weight of plant parts×concentration of nutrient within this tissues). This relation signifies the positive effect of improving the nutritional status of maize on increasing its growth. Results also reveal that the uptake values of all nutrients were negatively correlated with the changes that occurred in soil pH, while being positively correlated with each other. Although, chlorophyll content in plants was significantly correlated with plant dry weights; yet this parameter was not significantly affected by the uptake of the investigated soil macro- and micro- nutrients.

Table 1. Coefficient of determination “r^2” values calculated for the relation between maize dry weights, nutrient uptake by plants and soil pH .

	Total dry weights	Leaf chlorophyll	pH	P-uptake	K-uptake	Fe-uptake	Zn-uptake
Total dry weights							
Leaf chlorophyll	0.382*						
pH	-0.521**	-0.264					
P-uptake	0.317	0.345	-0.642**				
K-uptake	0.478*	0.111	-0.530**	0.660**			
Fe-uptake	0.515**	0.119	-0.740**	0.700**	0.584**		
Zn-uptake	0.518**	0.118	-0.754**	0.664**	0.512**	0.945**	

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

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

4. Discussion

4.1. Aplied biochars and maize growth parameters, soil pH, and nutrient availability

Application of non-acidified biochar was of no significant impacts on either Olsen-P or AB-DTPA extractable –Zn in soil. Despite being a source of nutrients that were set free upon its degradation (Zhang *et al.*, 2019); yet the availability of these nutrients might be affected negatively by its alkaline nature (See supplementary 1). Additionally, biochar had an amorphous porous structure which increased its surface area to retained more nutrients on its surfaces (Vahedi *et al*., 2022); thus, biochar application reduce available P (Nelson *et al*., 2011; Bornø *et al.*, 2018) and AB-DTPA-Zn (Hailegnaw *et al*., 2020).

On the other hand, mobile organic P-complexes may be formed owing to biocar applications (Chan *et al.*, 2007; Wang *et al*., 2012; Shen *et al.*, 2016; Elshony *et al.*, 2019; Pogorzelski *et al.*, 2020) that raised significantly P-uptake and distribution within maize parts. Thus, biochar acted as slow release fertilizers (Lustosa Filho *et al.*, 2019). On the other hand, this additive did not affect Zn content in shoots while decreased its content in roots.

This probably indicates that biochar boosted formation of soluble complexes with Zn (Karimi *et al.*, 2019) which increases its translocation within plants from roots to shoot (Elshony *et al.*, 2019). Our findings agree with the results of many researchers which indicate that biochar, in general, reduce the bioavailability of soil Zn in contaminated soil (Puga *et al.*, 2015; Rees *et al.*, 2015; Kumar *et al.*, 2018) while contradict those that indicate that biochar diminished its translocation to areal plant parts (Puga *et al.*, 2015; Eissa, 2019; Nzediegwu *et al.*, 2020). In case of Fe, this additive raised its content in roots, while did not affect its content in shoots. Probably, increased P content in soil and within plant roots stimulated Fe co-precipitation (Liu *et al.*, 2015) within plant roots (Jiang *et al.*, 2009) .

Application of acidified biochar decreased significantly soil pH (Peiris *et al.*, 2019) and this consequently raised the availability of some soil nutrients (Dai *et al.*, 2020) such as P, Fe and Zn (except K) beyond those attained for either BC or the control. These results agree, to some extent, with those recorded by Sahin *et al.* (2017) who indicate that the application of acid modified biochar raised significantly nutrient availability in a calcareous soil, e.g. P, K, Zn and Fe. This consequently upraised the uptake of the studied nutrients by maize plants. Soothar *et al.* (2021) and Khalil *et al*. (2023) found also that K availability and uptake increased by maize plants when being amended with acid modified biochar. Furthermore, Farid *et al.* (2025) notified the significant increases in P and K uptake by wheat plants when being supplied with acid modified biochar under salinity conditions. Neverthless, the increases in K uptake owing to the application of acidifed biochar were much lower than the corresponding ones found for the non-acidified one. There are two scenarios to explain such reductions. The first one is based on the increases of active sites on acidified biochars (Zeng *et al.*, 2022) that could retain more K. The second one is related to the increases that occurred in macro- and micro- cations availability in soil due to biochar application (Elshony *et al.*, 2019; Wang *et al.*, 2022) which may antagonize K influx to plant roots.

A point to note is that the SMBC treatment recorded significant reductions in Fe and Zn contents in roots probably due_to the dilution effect. Moreover, this additive contained S which may intensify the translocation of Fe and Zn from roots-to-shoots (Chorianopoulou *et al*., 2022; Shah *et al*., 2022). In this concern, many researches confirmed the positive impacts of acidified biochar on increasing uptake of these nutrients by plants, e.g. Fe and Zn by maize (Sahin *et al*., 2017) and Zn by bean, soybean, and maize (Taskin *et al*., 2019).

Overall, application of the two types of biochar improved the chlorophyll content in plants; yet only acidified biochar enhanced plant growth. These findings agree partially with Libutti *et al*.(2020), Abdelhafez *et al*. (2021), Farid *et al*.(2022), Jabbovora *et al* (2021) who recorded significant increases in plant growth and leaf chlorophyll for plants amended with biochar. On the other hand, Zhu *et al*. (2015) found that application of 10 g rice-straw-biochar kg^{-1} soil resulted in significant improvements in maize dry weights grown on only one type of studied soils while exhibited null or even negative impacts in the other 4 studied soil types. In another study, Ahmed *et al.* (2021) used 2 different types of biochars (greenwaste and corncob biochars) and their acidified forms in presence of 100% of the P-requirements and noticed that all treatments exhibited comparable dry weights of maize plants at the vegetative growth stage versus the control, except for greenwaste biochar and its acidified form as these two treatments decreased considerably plant dry weights. Based on the above results, the first hypothesis becomes acceptable.

4.2. Elemental sulfur and maize growth parameters, soil pH, and nutrient availability

Application of elemental S reduced significantly soil pH, especially with increasing its rate of application because elemental sulfur underwent oxidation in soil and increased soil acidity (Tabak *et al.*, 2020; Lee *et al.*, 2021). This acidity augmented the availability of the investigated soil nutrients. In this investigation, there were negative correlations between soil pH and all nutrient uptake by plants. Maybe, this acidity increased the solubility of Ca phosphates minerals in soil (Penn and Camberato, 2019) to set calcium free; hence increased P availability in soil (Glaser and Lehr, 2019) to be taken up by plants(Elshony *et al.*, 2019). Also, the availability of other soil nutrients, which are needed for proper plant growth, increased with increasing soil acidity (Nosheen *et al.*, 2021). For example, sulfur oxidation increased the solubility and reduction of Fe bearing minerals (Carvalhais *et al.*, 2011). Moreover, soluble ion pairs of $ZnSO_4$ were produced (Liu and Papangelakis, 2005; Wang *et al.*, 2016). The higher dose of applied S reduced significantly Fe availability because S addition also increased the availability of P (Carvalhais *et al.*, 2011) which might precipitate Fe (Kleeberg *et al.*, 2013; Wilfert *et al.*, 2015).

It is worth to mention that significant positive correlations were detected among the uptake of the investigated nutrients by maize plants, i.e. P, K, Fe and Zn. Such synergistic effects were previously confirmed by many researchers, i.e. P and K (Rietra *et al*., 2017; Hu *et al*., 2023), P and Zn (Rietra *et al*., 2017), P and Fe (Pii *et al*., 2015), K and Fe (Pii *et al*., 2015). Nonetheless, no synergistic or antagonistic effects were recorded between K and Zn uptake (Rietra *et al*., 2017). On the other hand, micro-nutrient availability declined considerably upon using high doses of either P (Abd El- Aziz *et al*., 2020; El-Shabasy *et la*., 2023; Nath et al., 2024) or K inputs(Li *et al*., 2020).

Doubtless, sulfur deficiency results in significant reductions in chlorophyll content (Samborska *et al*., 2019). Besides, S increases nutrient availability and uptake by plants (Pourbabaee *et al*., 2020); and this consequently upturns the net assimilation rate and plant growth (ur Rehman *et al*., 2013; Singh *et al*., 2018; Elsherpiny *et al*., 2024); nevertheless the rate of formation of chlorophyll seemed to be a bit slower (Vavilin *et al*., 2005) than plant growth rate and/or leaf chlorophyll was biosynthesised in sufficient amounts only to meet plant needs (Mandal and Dutta, 2020) rather than being excessively produced and accumulated in plant tissues (Hu *et al*., 2021; Luo *et al*., 2023) as a result of increasing nutrient intake. Thus, chlorophyll content was not significantly affected by S application rate versus the control. Similar findings indicate that chlorophyll content did not vary significantly in leaves of Spanish plants subjected to different fertigation levels for up to 4 weaks after planting (Nkcukankcuka *et al*., 2021).

Probably, K availability is less affected by soil pH verses the other investigated nutrients (Tabak *et a*l., 2020); yet at lower pH values, sorption of this metal ions on soil components decreased considerably while its desorption increased (Neina, 2019). This may explain the increases that took place in K content within plant parts owing to S application. Also, this amendment (elemental-S) enhanced the translocation of K from roots to shoots, probably as a counter ion via xylem loading and vacuolar storage in plant leaves (Reich *et al*., 2016). In case of Fe and Zn, S applications also increased their translocation from root to shoot. This is because S is involved in organic chelators (such as nicotianamine) which are responsible of Fe transport in both xylem and phloem (Astolfi *et al.*, 2021). Likewise, S is incorporated in the uptake and translocation of Zn within plants (Dede and Ozdemir, 2016).

Dry weights of maize shoots and roots were comparable in case of application of 1 g S kg^{-1} and the higher dose i.e. 2 g S kg^{-1}. Probably, the higher rate enhanced S uptake by plants via proton coupled co-transporters (Smith *et al.*, 2000; Buchner *et al.*, 2004); then rapidly transported to xylem where the majority is reduced(Maathuis, 2009). Accordingly, toxicity symptoms appears (Karthika *et al.*, 2018; Corpas and Palma, 2020) that downgraded plant growth (Palacio *et al*., 2014). The above results confirm the 2nd hypothesis.

4.3. Combined effect of biochar and elemental sulfur on maize growth parameters, soil pH, and nutrient availability

Applications of elemental S at a rate of 1 g kg^{-1} soil with either non-acidified biochar or the acidified one raised slightly the dry weights of maize shoots and roots; yet the only significant increases were detected in maize shoots. Probably, the pot size limited further root elongation and growth. Higher dose of elemental sulphur (2 g kg^{-1}) did not record further significant impacts on shoot and root dry weights versus the lower one (1 g kg^{-1}). Overall, SMBC (-/+ S) treatments recorded higher increases in maize biomases versus the ones that received normal biochar, even in presence of elemental sulphur at its highest application dose.

Results obtained herein indicate that acidified biochars effectively reduce soil pH to values exceeding those attained for biochar+ elemental S. This result agrees with Khalil *et al*. (2023). Besides, these additives (BC and SMBC) form soluble complexes with soil nutrients to increase their availability (Khalil *et al*., 2023; Taheri *et al*., 2023) and uptake by plants (Farid *et al*., 2025). Generally, the increases in plant biomasses were positively correlated with their uptake of soil nutrients.

Similar results indicate that the application of S with normal biochar declined soil pH. For example, Al-Rabaiai *et al*. (2024) found that soil pH was 8.05 when amended with biochar solely, then decreased to 7.65 when the soil received both S+biochar. Yet, the fast oxidation of elemental S in soil exists only within the first 28 days of application; thereafter S oxidation becomes slow (Yang *et al*., 2010), while soil restore its actual pH via its buffering ability (Wang *et al*., 2015). Thus, a single dose of elemental sulphur might not be deemed appropriate as an acidifying agent in soils of high buffering capacity.

5. Conclusion and Future Prospective

Sulfuric acid modified biochar exhibited better shoot growth and higher chlorophyll content than the dual application of biochar + elemental sulfur. In spite of that the latter treatment exhibited higher contents of K and Zn (but not Fe) in shoots. General, these results did not confirm the 3rd hypothesis which indicates that the relatively low cost additives (biochar+ elemental sulfur) on plant nutritional status and growth performance could be competent or even superior to the effect of the relatively expensive sulfuric acid modified biochar. May be elemental S should be applied in sucessive doses and this point should be considered in future studies.

Future perspectives are needed to find out the efficiencies of using different sources of biochar and their acid modified ones to increase production of different crops in arid soils under field conditions for more than 2 sucessive seasosn, while monitoring the changes in soil sustainability parameters and also evaluating the economic revenues of these treatments.

List of abbreviations:

NoBC: no added biochar

BC:normal biochar

SMBC: 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.

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References

Abd El- Aziz M, Abbas M, Ewis A (2020). Can humic acid alleviate the adverse effect of elevated phosphorus application on yield and nutritive contents of maize grown on a calcareous soil?. *Environment, Biodiversity and Soil Security*, *4*(Issue 2020), 333-343. https://doi.org/10.21608/jenvbs.2020.48032.1112

Abd El-Mageed TA, Belal EE, Rady MOA, Abd El-Mageed SA, Mansour E, Awad MF, Semida WM (2021) Acidified Biochar as a Soil Amendment to Drought Stressed (*Vicia faba* L.) Plants: Influences on Growth and Productivity, Nutrient Status, and Water Use Efficiency. Agronomy 11, 1290. https://doi.org/10.3390/agronomy11071290

Abdelhafez A, Abbas MHH, Li J (2017) Biochar: the black diamond for soil sustainability, contamination control and agricultural production. Engineering Applications of Biochar, pp. 7-27. https://doi.org/10.5772/intechopen.68803

Abdelhafez AA, Zhang X, Zhou L, Cai M, Cui N, Chen G, Zou G, Abbas MHH, Kenawy MHM, Ahmad M., Alharthi SS, Hamed, M.H (2021) Eco-friendly production of biochar via conventional pyrolysis: Application of biochar and liquefied smoke for plant productivity and seed germination. Environ. Technol. Innov. 22, 101540. https://doi.org/10.1016/j.eti.2021.101540

Abdelraof E, Nassar I, Gomaa I, Aboukila E (2023) Valorization of cheese whey as a fertilizer: Effects on maize germination and growth in clay loam and calcareous soil. *Egypt J Soil Sci*, *63*(4), 489-502. https://doi.org/10.21608/ejss.2023.222087.1620

Abuzaid A, Abdel-Salam M, Abbas M, Khalil F, Abdelhafez A (2025). Effectiveness of biochar and elemental sulfur for sustaining maize production in arid soils. *Egypt J Soil Sci*, *65*(1), -. https://doi.org/10.21608/ejss.2024.324620.1875

Agarwal H, Kashyap VH, Mishra A, Bordoloi S, Singh PK, Joshi NC (2022) Biochar-based fertilizers and their applications in plant growth promotion and protection. 3 Biotech 12, 136. https://doi.org/10.1007/s13205-022-03195-2

Ahmed N, Basit A, Bashir S *et al.* 2021: Effect of acidified biochar on soil phosphorus availability and fertilizer use efficiency of maize (Zea mays L.). *Journal of King Saud University - Science* **33,** 101635. https://doi.org/10.1016/j.jksus.2021.101635

Ali O, Abdelaal M (2020) Effect of Irrigation Intervals on Growth, Productivity and Quality of Some Yellow Maize Genotypes. Egypt J Agron 42, 105-122. https://doi.org/10.21608/agro.2020.26309.1207

Al-Rabaiai A, Menezes-Blackburn D, Al-Ismaily S *et al.* 2024: Biochar pH reduction using elemental sulfur and biological activation using compost or vermicompost. *Bioresour Technol* **401,** 130707. https://doi.org/10.1016/j.biortech.2024.130707

Asaad AA, El-Hawary AM, Abbas MHH, Mohamed I, Abdelhafez AA, Bassouny MA (2022) Reclamation of wastewater in wetlands using reed plants and biochar. Sci Rep 12, 19516. https://doi.org/10.1038/s41598-022-24078-9

Astolfi S, Celletti S, Vigani G, Mimmo T, Cesco S (2021) Interaction Between Sulfur and Iron in Plants. Front Plant Sci 12. https://doi.org/10.3389/fpls.2021.670308

Bashir MA, Naveed M, Ahmad Z, Gao B, Mustafa A, Núñez-Delgado A (2020) Combined application of biochar and sulfur regulated growth, physiological, antioxidant responses and Cr removal capacity of maize (*Zea mays* L.) in tannery polluted soils. Journal of Environmental Management 259, 110051. https://doi.org/10.1016/j.jenvman.2019.110051

Bassouny M, Abbas MHH (2019) Role of biochar in managing the irrigation water requirements of maize plants: the pyramid model signifying the soil Hydro-physical and environmental markers. Egypt J Soil Sci 59, 99-115. https://doi.org/10.21608/ejss.2019.9990.1252

Ben Hassen T, El Bilali H (2022) Impacts of the Russia-Ukraine War on Global Food Security: Towards More Sustainable and Resilient Food Systems? Foods 11, 2301. https://doi.org/10.3390/foods11152301

Bornø ML, Müller-Stöver DS, Liu F (2018) Contrasting effects of biochar on phosphorus dynamics and bioavailability in different soil types. Science of The Total Environment 627, 963-974. https://doi.org/10.1016/j.scitotenv.2018.01.283

Buchner P, Takahashi H, Hawkesford MJ (2004) Plant sulphate transporters: co-ordination of uptake, intracellular and long-distance transport. Journal of Experimental Botany 55, 1765-1773. https://doi.org/10.1093/jxb/erh206

Burrell LD, Zehetner F, Rampazzo N, Wimmer B, Soja G (2016) Long-term effects of biochar on soil physical properties. Geoderma 282, 96-102. https://doi.org/10.1016/j.geoderma.2016.07.019

Carvalhais LC, Dennis PG, Fedoseyenko D, Hajirezaei M-R, Borriss R, von Wirén N (2011) Root exudation of sugars, amino acids, and organic acids by maize as affected by nitrogen, phosphorus, potassium, and iron deficiency. J Plant Nutr Soil Sci 174, 3-11. https://doi.org/10.1002/jpln.201000085

Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2007) Agronomic values of greenwaste biochar as a soil amendment. Soil Res 45, 629-634. https://doi.org/10.1071/SR07109

Chen W, Meng J, Han X, Lan Y, Zhang W (2019) Past, present, and future of biochar. Biochar 1, 75-87. https://doi.org/10.1007/s42773-019-00008-3

Chew J, Joseph S, Chen G, Zhang Y, Zhu L, Liu M, Taherymoosavi S, Munroe P, Mitchell DRG, Pan G, Li L, Bian R, Fan X (2022) Biochar-based fertiliser enhances nutrient uptake and transport in rice seedlings. Sci Total Environ 826, 154174. https://doi.org/10.1016/j.scitotenv.2022.154174

Choppala G, Kunhikrishnan A, Seshadri B, Park JH, Bush R, Bolan N (2018) Comparative sorption of chromium species as influenced by pH, surface charge and organic matter content in contaminated soils. J. Geochem. Explor. 184, 255-260. https://doi.org/10.1016/j.gexplo.2016.07.012

Chorianopoulou SN, Bouranis DL (2022) The Role of Sulfur in Agronomic Biofortification with Essential Micronutrients. *Plants*. 11(15):1979. https://doi.org/10.3390/plants11151979

Corpas FJ, Palma JM (2020) H_2S signaling in plants and applications in agriculture. J Adv Res 24, 131-137. https://doi.org/10.1016/j.jare.2020.03.011

Dai Y, Zheng H, Jian, Z, Xing B (2020) Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis. Science of The Total Environment 713, 136635. https://doi.org/10.1016/j.scitotenv.2020.136635

Dede G, Ozdemir S (2016) Effects of elemental sulphur on heavy metal uptake by plants growing on municipal sewage sludge. J Environ Manage 166, 103-108. https://doi.org/10.1016/j.jenvman.2015.10.015

Devereux RC, Sturrock CJ, Mooney SJ (2012) The effects of biochar on soil physical properties and winter wheat growth. Earth and Environmental Earth Environ. Sci. Trans. R. Soc. Edinb. 103, 13-18. https://doi.org/10.1017/s1755691012000011

Eissa MA (2019) Effect of cow manure biochar on heavy metals uptake and translocation by zucchini (*Cucurbita pepo* L). Arab J Geosci 12, 48. https://doi.org/10.1007/s12517-018-4191-1

Eliw M, Negm M, Sami R, Algarni E, Alshehry G, Aljumayi H, Benajiba N, Al-Mushhin, AAM, Bahloul AME (2022). Dynamic modeling of food security in the light of reality and the future: The case of maize crop. J. Biobased Mater. Bioenergy 16, 24-37. . https://doi.org/10.1166/jbmb.2022.2157

El-Nagar DA, Sary DH (2021) Synthesis and characterization of nano bentonite and its effect on some properties of sandy soils. Soil Till Res 208, 104872. https://doi.org/10.1016/j.still.2020.104872

El-Shabasy S, Hamissa A E, Talha N, El-Basuny A (2023). Effect of different phosphate fertilizers on the availability of some heavy metals in El-Gabal El Asfer soil under maize and wheat cropping system. *Egypt J Soil Sci*, *63*(3), 267-275. https://doi.org/10.21608/ejss.2023.196968.1574

El-Sharkawy M, El-Naggar AH, AL-Huqail AA, Ghoneim AM (2022) Acid-modified biochar impacts on soil properties and biochemical characteristics of crops grown in saline-sodic soils. Sustainability 14, 8190. https://doi.org/10.3390/su14138190

Elsherpiny, M., baddour, A., EL-Shaboury, H. (2024). Unveiling the synergistic role of elemental sulfur, potassium supplements and methionine in improving yield and quality of onion. *Egypt J Soil Sci*, *64*(4), 1419-1431. https://doi.org/10.21608/ejss.2024.296109.1788

Elshony M, Farid IM, Alkamar F, Abbas MHH, Abbas HH (2019) Ameliorating a sandy soil using biochar and compost amendments and their implications as slow release fertilizers on plant growth. Egypt J Soil Sci 59, 305-322. https://doi.org/10.21608/ejss.2019.12914.1276

Farid Y, Ali, I., Abdelhafez A, Abbas M (2025) Enhancing wheat productivity in salt-affected soils using traditional and acidified biochars: A sustainable solution. *Egypt J Soil Sci*, *65*(1), -. https://doi.org/10.21608/ejss.2024.325183.1869

Farid IM, El-Nabarawy A, Abbas MHH, Morsy A, Afifi M, Abbas H, Hekal M (2021) Implications of seed irradiation with γ-rays on the growth parameters and grain yield of faba bean. Egypt J Soil 61, 175-186. https://doi.org/10.21608/ejss.2021.58054.1424

Farid IM, Siam HS, Abbas MHH, Mohamed I, Mahmoud SA, Tolba M, Abbas HH, Yang X, Antoniadis V, Rinklebe J, Shaheen SM (2022) Co-composted biochar derived from rice straw and sugarcane bagasse improved soil properties, carbon balance, and zucchini growth in a sandy soil: A trial for enhancing the health of low fertile arid soils. Chemosphere 292, 133389. https://doi.org/10.1016/j.chemosphere.2021.133389

Fidel RB, Laird DA, Spokas KA (2018) Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. Sci Rep 8, 17627. https://doi.org/10.1038/s41598-018-35534-w

Glaser B, Lehr V-I (2019) Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. Sci Rep 9, 9338. https://doi.org/10.1038/s41598-019-45693-z

Gotteni A, Verloo L, Camerlynch G (1982) Chemical analysis of soil lap of analytical and agro chemistry. State Univ. Ghent, Belgium.

Haider FU, Coulter JA, Cai L, Hussain S, Cheema SA, Wu J, Zhang R (2022) An overview on biochar production, its implications, and mechanisms of biochar-induced amelioration of soil and plant characteristics. Pedosphere 32, 107-130. https://doi.org/10.1016/S1002-0160(20)60094-7

Hailegnaw NS, Mercl F, Pračke K, Praus L, Száková J, Tlustoš P (2020) The Role of Biochar and Soil Properties in Determining the Available Content of Al, Cu, Zn, Mn, and Cd in Soil. *Agronomy* 10(6):885. https://doi.org/10.3390/agronomy10060885

Hegab, R. (2024). Impact of integrating between mineral nitrogen, vermicompost and biochar on nitrogen-use efficiency and productivity of panicum plants grown on sandy soil. *Egypt J Soil Sci*, *64*(3), 1273-1284. https://doi.org/10.21608/ejss.2024.291453.1777

Hossain MZ, Bahar MM, Sarkar B, Donne SW, Ok YS, Palansooriya KN, Kirkham MB, Chowdhury S, Bolan N (2020) Biochar and its importance on nutrient dynamics in soil and plant. Biochar 2, 379-420. https://doi.org/10.1007/s42773-020-00065-z

Hou J, Pugazhendhi A, Sindhu R, Vinayak V, Thanh NC, Brindhadevi K, Lan Chi NT, Yuan D (2022) An assessment of biochar as a potential amendment to enhance plant nutrient uptake. Environ Res 214, 113909. https://doi.org/10.1016/j.envres.2022.113909

Hu W, Wang J, Deng Q, Liang D, Xia H, Lin L, Lv X (2023) Effects of different types of potassium fertilizers on nutrient uptake by grapevine. *Horticulturae*. 9(4):470. https://doi.org/10.3390/horticulturae9040470

Hu X, Gu T, Khan I, Zada A, Jia T (2021) Research Progress in the Interconversion, Turnover and Degradation of Chlorophyll. *Cells*. 2021; 10(11):3134. https://doi.org/10.3390/cells10113134

Huang W-H, Lee D-J, Huang C (2021) Modification on biochars for applications: A research update. Bioresour Technol 319, 124100. https://doi.org/10.1016/j.biortech.2020.124100

Jabborova D, Wirth S, Halwani M, Ibrahim MFM, Azab I.H.E., El-Mogy, M.M., Elkelish, A (2021) Growth response of ginger (*Zingiber officinale*), its physiological properties and soil enzyme activities after biochar application under greenhouse conditions. Horticulturae 7, 250. https://doi.org/10.3390/horticulturae7080250

Jiang FY, Chen X, Luo AC (2009) Iron plaque formation on wetland plants and its influence on phosphorus, calcium and metal uptake. Aquatic Ecology 43, 879-890. https://doi.org/10.1007/s10452-009-9241-z

Karimi A, Moezzi A, Chorom M, Enayatizamir N (2019) Chemical Fractions and Availability of Zn in a Calcareous Soil in Response to Biochar Amendments. J Soil Sci Plant Nutr 19, 851-864. https://doi.org/10.1007/s42729-019-00084-1

Karthika KS, Rashmi I, Parvathi MS (2018) Biological Functions, Uptake and Transport of Essential Nutrients in Relation to Plant Growth. In: Hasanuzzaman, M., Fujita, M., Oku, H., Nahar, K., Hawrylak-Nowak, B. (Eds.), Plant Nutrients and Abiotic Stress Tolerance. Springer Singapore, Singapore, pp. 1-49.https://doi.org/10.1007/978-981-10-9044-8_1

Khalil F, Abdel-Salam M, Abbas M, Abuzaid, A. (2023). Implications of acidified and non-acidified biochars on N and K availability and their uptake by maize plants. *Egypt J Soil Sci*, *63*(1), 101-112. https://doi.org/10.21608/ejss.2023.184654.1560

Kleeberg A, Herzog C, Hupfer M (2013) Redox sensitivity of iron in phosphorus binding does not impede lake restoration. Water Research 47, 1491-1502. https://doi.org/10.1016/j.watres.2012.12.014

Klute A (1986) Part 1. Physical and mineralogical methods. ASA-SSSA-Agronomy, Madison, Wisconsin USA.

Kocsis T, Ringer M, Biró B (2022) Characteristics and Applications of Biochar in Soil–Plant Systems: A Short Review of Benefits and Potential Drawbacks. Applied Sciences 12, 4051. https://doi.org/10.3390/app12084051

Kumar A, Joseph S, Tsechansky L, Privat K, Schreiter IJ, Schüth C, Graber ER (2018) Biochar aging in contaminated soil promotes Zn immobilization due to changes in biochar surface structural and chemical properties. Sci Total Environ 626, 953-961. https://doi.org/10.1016/j.scitotenv.2018.01.157

Lee S-Y, Kim E-G, Park J-R, Ryu Y-H, Moon W, Park G-H, Ubaidillah M, Ryu S-N, Kim K-M (2021) Effect on chemical and physical properties of soil each peat moss, elemental sulfur, and sulfur-oxidizing bacteria. Plants 10, 1901. https://doi.org/10.3390/plants10091901

Li Z, Liu Z, Zhang M, Li C, Li YC, Wan Y, Martin CG (2020) Long-term effects of controlled-release potassium chloride on soil available potassium, nutrient absorption and yield of maize plants. *Soil Till Res* **196,** 104438. https://doi.org/10.1016/j.still.2019.104438

Libutti A, Trotta V, Rivelli AR (2020) Biochar, vermicompost, and compost as soil organic amendments: Influence on growth parameters, nitrate and chlorophyll content of swiss Cchard (*Beta vulgaris* L. var. cycla). Agronomy 10, 346. https://doi.org/10.3390/agronomy10030346

Liu F, Zuo J, Chi T, Wang P, Yang B (2015) Removing phosphorus from aqueous solutions by using iron-modified corn straw biochar. **Front.** Environ. Sci. Eng. 9, 1066-1075. https://doi.org/10.1007/s11783-015-0769-y

Liu H, Papangelakis VG (2005) Thermodynamic equilibrium of the O_2–$ZnSO_4$–H_2SO_4–H_2O system from 25 to 250°C. Fluid Phase Equilibria 234, 122-130. https://doi.org/10.1016/j.fluid.2005.06.004

Luo WG, Liang QW, Su Y, Huang C, Mo BX, Yu Y, Xiao LT (2023) Auxin inhibits chlorophyll accumulation through ARF7-IAA14-mediated repression of chlorophyll biosynthesis genes in *Arabidopsis*. Front Plant Sci. 20(14), 1172059. https://doi.org/10.3389/fpls.2023.1172059

Lustosa Filho JF, Barbosa CF, Carneiro JSdS, Melo LCA (2019) Diffusion and phosphorus solubility of biochar-based fertilizer: Visualization, chemical assessment and availability to plants. Soil Till Res 194, 104298. https://doi.org/10.1016/j.still.2019.104298

Ma H, Shurigin V, Jabborova D, dela Cruz JA, dela Cruz TE, Wirth S, Bellingrath-Kimura SD, Egamberdieva D (2022) The Integrated Effect of Microbial Inoculants and Biochar Types on Soil Biological Properties, and Plant Growth of Lettuce (Lactuca sativa L.). Plants 11, 423. https://doi.org/10.1016/j.pbi.2009.04.003

Maathuis FJM (2009) Physiological functions of mineral macronutrients. Curr. Opin. Plant Biol. 12, 250-258. https://doi.org/10.1016/j.pbi.2009.04.003

Malik L, Sanaullah M, Mahmood F, Hussain S, Siddique MH, Anwar F, Shahzad T (2022) Unlocking the potential of co-applied biochar and plant growth-promoting rhizobacteria (PGPR) for sustainable agriculture under stress conditions. Chem Biol Technol Agric 9, 58. https://doi.org/10.1186/s40538-022-00327-x

Mandal R, Dutta G (2020) From photosynthesis to biosensing: Chlorophyll proves to be a versatile molecule. *Sensors International* **1,** 100058. https://doi.org/10.1016/j.sintl.2020.100058

Mattiello EM, da Silva RC, Degryse F, Baird R, Gupta VVSR, McLaughlin MJ (2017) Sulfur and zinc availability from co-granulated Zn-enriched elemental sulfur fertilizers. J. Agric. Food Chem. 65, 1108-1115. https://doi.org/10.1021/acs.jafc.6b04586

Mekawy MMM, Gmail MEA (2022) Economic analysis of supply response of summer maize crop in Egypt. Egypt. J. Agric. Res. 100, 271-283. https://doi.org/10.21608/ejar.2022.128812.1219

Nkcukankcuka M, Jimoh MO, Griesel G, Laubscher CP (2021) Growth characteristics, chlorophyll content and nutrients uptake in *Tetragonia decumbens* Mill. cultivated under different fertigation regimes in hydroponics, Crop and Pasture Science, 73(2), 67-76, https://doi.org/10.1071/CP2051

Morone P, Koutinas A, Gathergood N, Arshadi M, Matharu A (2019) Food waste: Challenges and opportunities for enhancing the emerging bio-economy. J Cleaner Prod 221, 10-16. https://doi.org/10.1016/j.jclepro.2019.02.258

Murtaza G, Ahmed Z, Usman M (2022) Feedstock type, pyrolysis temperature and acid modification effects on physiochemical attributes of biochar and soil quality. Arab J Geosci 15, 305. https://doi.org/10.1007/s12517-022-09539-9

Nath S, Dey S, Kundu R, Paul S (2024) Phosphate and zinc interaction in soil and plants: a reciprocal cross-talk. *Plant Growth Regul* **104**, 591–615. https://doi.org/10.1007/s10725-024-01201-6

Neina, D (2019) The role of soil pH in plant nutrition and soil remediation. Appl. Environ. Soil Sci. 2019, 5794869. https://doi.org/10.1155/2019/5794869

Nelson NO, Agudelo SC, Yuan, WGJ (2011) Nitrogen and Phosphorus Availability in Biochar-Amended Soils. Soil Sci 176(5):p 218-226, May 2011. https://doi.org/10.1097/SS.0b013e3182171eac

Niel EM (2021) Effect of Organic and nitrogen fertilizers on soil fertility and wheat productivity in a newly reclaimed sandy soil. Alex Sci Exch J 42, 573-582. https://doi.org/10.21608/asejaiqjsae.2021.182596

Nosheen S, Ajmal I, Song Y (2021) Microbes as Biofertilizers, a Potential Approach for Sustainable Crop Production. Sustainability 13, 1868. https://doi.org/10.3390/su13041868

Nzediegwu C, Prasher S, Elsayed E, Dhiman J, Mawof A, Patel R (2020) Impact of Soil Biochar Incorporation on the Uptake of Heavy Metals Present in Wastewater by Spinach Plants. Water, Air, & Soil Pollution 231, 123. . https://doi.org/10.1007/s11270-020-04512-2

Ojha S, Bußler S, Schlüter OK (2020) Food waste valorisation and circular economy concepts in insect production and processing. Waste Manage 118, 600-609. https://doi.org/10.1016/j.wasman.2020.09.010

Palacio S, Aitkenhead M, Escudero A, Montserrat-Martí G, Maestro M, Robertson AHJ (2014) Gypsophile Chemistry Unveiled: Fourier Transform Infrared (FTIR) Spectroscopy Provides New Insight into Plant Adaptations to Gypsum Soils. PLOS ONE 9, e107285. https://doi.org/10.1371/journal.pone.0107285

Peiris C, Nayanathara O, Navarathna CM, Jayawardhana Y, Nawalage S, Burk G, Karunanayake AG, Madduri SB, Vithanage M, Kaumal MN, Mlsna TE, Hassan EB, Abeysundara S, Ferez F, Gunatilake SR (2019) The influence of three acid modifications on the physicochemical characteristics of tea-waste biochar pyrolyzed at different temperatures: a comparative study. RSC Advances 9, 17612-17622. https://doi.org/10.1039/c9ra02729g

Penn CJ, Camberato JJ (2019) A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agriculture 9, 120. https://doi.org/10.3390/agriculture9060120

Pii Y, Cesco S, Mimmo T (2015) Shoot ionome to predict the synergism and antagonism between nutrients as affected by substrate and physiological status. *Plant Physiol Biochem* **94,** 48-56. https://doi.org/10.1016/j.plaphy.2015.05.002

Pogorzelski D, Filho JFL, Matias PC, Santos WO, Vergütz L, Melo LCA (2020) Biochar as composite of phosphate fertilizer: Characterization and agronomic effectiveness. Sci Total Environ 743, 140604. https://doi.org/10.1016/j.scitotenv.2020.140604

Pourbabaee AA, Koohbori Dinekaboodi S, Seyed Hosseini HM, Alikhani HA, Emami S (2020) Potential application of selected sulfur-oxidizing bacteria and different sources of sulfur in plant growth promotion under different moisture conditions. Comm Soil Sci Plant Anal 51, 735-745. https://doi.org/10.1080/00103624.2020.1729377

Puga AP, Abreu CA, Melo LCA, Beesley L (2015) Biochar application to a contaminated soil reduces the availability and plant uptake of zinc, lead and cadmium. J Environ Mana 159, 86-93. https://doi.org/10.1016/j.jenvman.2015.05.036

Rees F, Germain C, Sterckeman T, Morel J-L (2015) Plant growth and metal uptake by a non-hyperaccumulating species (*Lolium perenne*) and a Cd-Zn hyperaccumulator (*Noccaea caerulescens*) in contaminated soils amended with biochar. Plant Soil 395, 57-73. https://doi.org/10.1007/s11104-015-2384-x

Reich M, Shahbaz M, Prajapati DH, Parmar S, Hawkesford MJ, De Kok LJ (2016) Interactions of sulfate with other nutrients as revealed by H_2S fumigation of chinese cabbage. Front Plant Sci 7. https://doi.org/10.3389/fpls.2016.00541

Rietra, RPJJ, Heinen M, Dimkpa C. O., & Bindraban, P. S. (2017) Effects of Nutrient Antagonism and Synergism on Yield and Fertilizer Use Efficiency. *Communications in Soil Science and Plant Analysis*, *48*(16), 1895–1920. https://doi.org/10.1080/00103624.2017.1407429

Sahin O, Taskin MB, Kaya EC, Atakol O, Emir E, Inal A. Gunes A (2017), Effect of acid modification of biochar on nutrient availability and maize growth in a calcareous soil. Soil Use Manage, 33: 447-456. https://doi.org/10.1111/sum.12360

Samborska IA, Kalaji HM, Sieczko L, Borucki W, Mazur R, Kouzmanova M, Goltsev V (2019) Can just one-second measurement of chlorophyll a fluorescence be used to predict sulphur deficiency in radish (*Raphanus sativus* L. sativus) plants? Curr Plant Biolo 19, 100096. https://doi.org/10.1016/j.cpb.2018.12.002

Shah SH, Islam, S, Mohammad F (2022) Sulphur as a dynamic mineral element for plants: a review. *J Soil Sci Plant Nutr* **22**, 2118–2143. https://doi.org/10.1007/s42729-022-00798-9

Shen Q, Hedley M, Camps Arbestain M, Kirschbaum MUF (2016) Can biochar increase the bioavailability of phosphorus? J. Soil Sci. Plant Nutr. 16, 268-286. http://dx.doi.org/10.4067/S0718-95162016005000022

Singh SK, Sharma M, Reddy KR, Venkatesh T (2018) Integrated application of boron and sulphur to improve quality and economic yield in potato. J Environ Biol (Lucknow) 39, 204-210. https://doi.org/10.22438/jeb/39/2/MRN-395

Smith FW, Rae AL, Hawkesford MJ (2000) Molecular mechanisms of phosphate and sulphate transport in plants. Biochim. Biophys. Acta - Biomembr 1465, 236-245. https://doi.org/10.1016/S0005-2736(00)00141-3

Soltanpour PN (1985) Use of ammonium bicarbonate DTPA soil test to evaluate elemental availability and toxicity. Comm Soil Sci Plant Anal 16, 323-338. https://doi.org/10.1080/00103628509367607

Soothar MK, Mounkaila Hamani AK, Kumar Sootahar M, Sun J, Yang G, Bhatti SM, Traore A (2021) Assessment of acidic biochar on the growth, physiology and nutrients uptake of maize (*Zea mays* L.) seedlings under salinity stress. *Sustainability*. 13(6):3150. https://doi.org/10.3390/su13063150

Sparks DL, Page AL, Helmke PA, Loeppert RH, (2020) Methods of Soil Analysis Part 3—Chemical Methods. 5.3. SSSA Book Series 5, Madison, WI.

Sun C, Sun J, Gao J, Liu J, Yu X, Wang Z, Yang X, Ji N (2022) Comprehensive application of bio-char and nitrogen fertilizer in dry-land maize cultivation. Sci Rep 12, 13478. https://doi.org/10.1038/s41598-022-16971-0

Tabak M, Lisowska A, Filipek-Mazur B, Antonkiewicz J (2020) The effect of amending soil with waste elemental sulfur on the availability of selected macroelements and heavy metals. Processes 8, 1245. https://doi.org/10.3390/pr8101245

Taheri MaR, Astaraei AR, Lakzian A, Emami H (2024) The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil. *Plant Soil* **499**, 221–236. https://doi.org/10.1007/s11104-023-05912-z

Taskin MB, Kadioglu YK, Sahin O, Inal A, Gunes A (2019) Effect of acid modified biochar on the growth and essential and non- essential element content of bean, chickpea, soybean, and maize grown in calcareous soil. *Communications in Soil Science and Plant Analysis*, *50*(13), 1604–1613. https://doi.org/10.1080/00103624.2019.1631326

Tolba M, Farid IM, Siam H, Abbas MHH, Mohamed I, Mahmoud S, El-Sayed AE-K (2021) Integrated management of K - additives to improve the productivity of zucchini plants grown on a poor fertile sandy soil. Egypt J Soil Sci 61, 355-365. https://doi.org/10.21608/ejss.2021.99643.1472

ur Rehman H, Iqbal Q, Farooq M, Wahid A, Afzal I, Basra SMA (2013) Sulphur application improves the growth, seed yield and oil quality of canola. Acta Physiol Plant 35, 2999-3006. https://doi.org/10.1007/s11738-013-1331-9

Vahedi R, Rasouli-Sadaghiani MH, Barin M, Vetukuri RR (2022) Effect of Biochar and Microbial Inoculation on P, Fe, and Zn Bioavailability in a Calcareous Soil. *Processes.* 10(2):343. https://doi.org/10.3390/pr10020343

van Hoof L, Fabi G, Johansen V, Steenbergen J, Irigoien X, Smith S, Lisbjerg D, Kraus G (2019) Food from the ocean; towards a research agenda for sustainable use of our oceans' natural resources. Marine Policy 105, 44-51. https://doi.org/10.1016/j.marpol.2019.02.046

Vavilin D, Brune DC, Vermaas W (2005) 15N-labeling to determine chlorophyll synthesis and degradation in Synechocystis sp. PCC 6803 strains lacking one or both photosystems. *Biochimica et Biophysica Acta (BBA) - Bioenergetics* **1708,** 91-101. https://doi.org/10.1016/j.bbabio.2004.12.011

Vithanage M, Rajapaksha AU, Zhang M, Thiele-Bruhn S, Lee SS, Ok YS (2015) Acid-activated biochar increased sulfamethazine retention in soils. Environ. Sci. Pollut. Res. 22, 2175-2186. https://doi.org/10.1007/s11356-014-3434-2

Wang X, Tang C, Mahony S, Baldock JA, Butterly CR (2015), Factors affecting the measurement of soil pH buffer capacity: approaches to optimize the methods. Eur J Soil Sci, 66: 53-64. https://doi.org/10.1111/ejss.12195

Wang T, Camps-Arbestain M, Hedley M, Bishop P (2012) Predicting phosphorus bioavailability from high-ash biochars. Plant and Soil 357, 173-187. https://doi.org/10.1007/s11104-012-1131-9

Wang X, Wan Y, Hu W, Chou IM, Cao J, Wang X, Wang M, Li Z (2016) In situ observations of liquid–liquid phase separation in aqueous ZnSO4 solutions at temperatures up to 400°C: Implications for Zn2+–SO_4^{2-} association and evolution of submarine hydrothermal fluids. Geochim. Cosmochim. Acta 181, 126-143. https://doi.org/10.1016/j.gca.2016.03.001

Wang Z, Pan X, Kuang S, Chen C, Wang X, Xu J, Li X, Li H, Zhuang Q, Zhang F, Wang X (2022) Amelioration of coastal salt-affected soils with biochar, acid modified biochar and wood vinegar: Enhanced nutrient availability and bacterial community modulation. Int. J. Environ. Res. Public Health 19, 7282. https://doi.org/10.3390/ijerph19127282

Wilfert P, Kumar PS, Korving L, Witkamp G-J, van Loosdrecht MCM (2015) The Relevance of Phosphorus and Iron Chemistry to the Recovery of Phosphorus from Wastewater: A Review. Environ Sci Technol 49, 9400-9414. https://doi.org/10.1021/acs.est.5b00150

Yang Z-H, StÖVen K, Haneklaus S, Singh BR & Schnug E 2010: Elemental Sulfur Oxidation by Thiobacillus spp. and Aerobic Heterotrophic Sulfur-Oxidizing Bacteria. *Pedosphere* **20,** 71-79. https://doi.org/10.1016/S1002-0160(09)60284-8

Zeng X-Y, Wang Y, Li R-X, Cao H-L, Li Y-F, Lü J (2022) Impacts of temperatures and phosphoric-acid modification to the physicochemical properties of biochar for excellent sulfadiazine adsorption. Biochar 4, 14. https://doi.org/10.1007/s42773-022-00143-4

Zhang R, Zhao Y, Lin J, Hu Y, Hänninen H, Wu J (2019) Biochar application alleviates unbalanced nutrient uptake caused by N deposition in Torreya grandis trees and seedlings. For Ecol Manag 432, 319-326. https://doi.org/10.1016/j.foreco.2018.09.040

Zhu Q, Peng X, Huang T (2015) Contrasted effects of biochar on maize growth and N use efficiency depending on soil conditions. Int. Agrophys. 29(2):257-266. https://doi.org/10.1515/intag-2015-0023