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ORIGINAL RESEARCH

Effect of the co-application of olive waste-based compost and biochar on soil fertility and *Zea mays* agrophysiological traits

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Abstract

Purpose The deterioration of agricultural soil can be alleviated by maintaining an appropriate level of soil organic matter by using organic amendments such as compost and biochar. The aim of this study was to investigate the effects of olive waste-based compost, wood-based biochar and their combination on the chemical and microbial properties of loamy clay soil and the agrophysiological traits of maize.

Method *Zea mays* was grown under greenhouse conditions for 3 months in pots filled with alkaline soil collected from 0-30 cm depth. The experiment was arranged in a completely randomized design with 5 replicates and 3 treatments: compost-soil [1:10 (v/v)], biochar-soil [1:20 (v/v)] and (1:2)-ratio biochar-compost combination (BCC).

Results Biochar addition singly or in BCC increased soil TOC, EC, and pH. Furthermore, adding biochar to compost increased the levels of macro- and micronutrients compared to those under single application of biochar. The soil fertility improved significantly with regard to available phosphorus and potassium, nitrogen, and micronutrients. Single application of biochar had a negative impact on mycorrhizal symbiosis and was statistically insignificant for soil viable cultivable microorganisms.

Conclusion Overall, single application of compost gave the best results in terms of plant growth and soil fertility improvement; thus, a synergistic effect of both amendments was not observed, which could be due to the quantity of the applied biochar and the duration of the experiment.

Keywords Compost, Biochar, Maize, *Arbuscular mycorrhizal* fungi, Nutrient availability

Introduction

Fulfilling the nutritional needs of the exponentially growing world population, which is estimated to reach 9 billion by 2050, will require increasing agricultural productivity by almost 70% (WPP 2017). The green revolution resulted in several technological advances in both chemistry and agriculture, thus leading to the implementation of intensive agricultural models, which significantly improved the yield of economically important crops. Nonetheless, such highly productive systems proved to have some critical drawbacks related to sustainable fertility management. In the current eco-environmental context, the deterioration of soil fertility is one of most pressing issues facing agricultural productivity, and according to a report of the Global Environment Facility (GEF 2008), the depletion of soil nutrient reserves is mainly attributed to soil organic matter deficiency. Africa is peculiarly affected by this phenomenon, and it is estimated that more than 60% of African arable lands are subjected to soil degradation. Furthermore, approximately 6 million hectares of arable land are lost each year due to soil degradation, leading to approximately $65 million/year of losses (GEF 2008).

Maintaining an appropriate level of soil organic matter is important as it ensures efficient biological cycling of nutrients, which contributes to sustainable

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management of soil and agricultural productivity. Several approaches can be exploited to improve soil organic matter, including cropping-related practices (rotation and intercropping). According to Rasmussen et al. (1998), conventional tillage practices could reduce soil organic carbon at a soil depth of 0–7.5 cm by 25% to 30% compared to continuous crop harvesting, and this impact could be significantly minimized using organic amendments such as composts and biochar. Such organic inputs are particularly promising, as they are obtained by processing organic waste, which is in line with the circular economy concept. Indeed, the use of soil organic amendment is a sustainable approach that has largely proven its efficacy in improving the physico-chemical and biological properties of poor soils. Amending soil with carbon-rich organic products is not strictly correlated with soil fertility, which depends on several features, including the soil type, the properties of the raw materials and the processing methodology (Bastida et al. 2015; Abbas et al. 2017; Qayyum et al. 2017; Amoah-Antwi et al. 2020; Carabassa et al. 2020). Nevertheless, organic amendment provides many direct and indirect benefits for crop productivity, such as improving soil structure and stability, reducing erosion vulnerability, increasing microbial activity and diversity, and enhancing nutrient availability and water retention capacity.

Biochar and compost are two organic products that are frequently used to improve/restore the content of soil organic matter. Biochar is a black carbon-rich material resulting from the thermo-chemical decomposition of biomass such as grasses, wood crop residue and animal residue under anaerobic conditions (Spokas et al. 2010). On the other hand, compost is produced via aerobic microbial degradation of biomass, including municipal and agro-industrial waste. Olive mill waste-based compost is particularly interesting, and several studies have reported the advantages of such products over compost produced by processing sewage sludge and poultry manure, as olive mill waste-based compost is not subject to contamination by heavy metals, antibiotics and pathogens (Barje et al. 2012; El Fels et al. 2014; Zhang et al. 2019; Bouhia et al. 2020). Recently, biochar has attracted the attention of both scientists and industry due to its high functional diversity in many environmental conditions. For example, biochar application in agriculture is directly linked to changes in soil chemical and textural features, which often improves the soil water holding capacity and fertilizer use efficiency by enhancing nutrient bioavailability and reducing leaching (Thangarajan et al. 2018; Manolikaki and Diamadopoulos 2019). The positive effect of biochar on soil properties and nutritional status is plausibly attributed to the formation of organo-mineral complexes and the alteration of phosphorus sorption/desorption equilibrium (Gao et al. 2017). The contribution of biochar to soil carbon sequestration is significant, as it is characterized by a high residence time, which can range from tens of years to millennia (Verheijen et al. 2010; Malghani et al. 2013). Notably, depending on the raw materials used and pyrolysis conditions, biochar may display several negative aspects, including an alkaline pH and a high C:N ratio due to the abundance of lignocellulosic fractions and a poor nutrient content when wood is used as raw material, which is often the case (Ronsse et al. 2013; Chintala et al. 2014). Furthermore, depending on the porosity and specific surface traits of biochar, its effect on soil enzymatic activity and indigenous microbes is highly variable and could be either negative or positive (Farrell et al. 2013; Tang et al. 2020). For example, Rutigliano et al. (2014) showed that the application of wood-based biochar at rates of 30 and 60 t ha^{-1} significantly reduced the changes in functional microbial diversity and biomass carbon compared to the change in total soil organic carbon, thus showing that only a small portion of the organic carbon could be readily metabolized. Additionally, other studies showed that the application of higher doses of biochar can reduce the mycorrhizal traits of plants, including colonization percentage and mycorrhizal frequency (Warnock et al. 2007; George et al. 2012).

Several studies have addressed the effect of single application of biochar or compost on soil properties and plant development. To the best of our knowledge, studies investigating simultaneous application of both amendments are still scarce, despite their theoretical complementarity with respect to composition, functional properties, and positive effects on plant growth. Therefore, the aim of this study was to evaluate the effect of the co-application of a wood-based biochar and compost generated from olive mill wastewater sludge (OMWS) processing on soil physicochemical properties, macro- and micronutrient availability and *Zea mays* agrophysiological traits. Moreover, the effect of single and co-application of both organic amendments on soil cultivable microorganisms as well as the effect on arbuscular mycorrhizal fungi (AMF) colonization was investigated. Overall, we hypothesize that such a co-application strategy could operate synergistically, thus enhancing the functionality of the whole soil-microbe-plant system.

Materials and methods

Organic amendment preparation

The feedstock for compost production was collected from a semi-modern olive oil production unit located in Chichaoua in the Marrakech-Safi region, Morocco. This waste was generated in a large quantity and in stabilized form using natural and forced evaporation. Composting was carried out in a bioreactor with a capacity of 100 L by mixing OMWS, green waste (GW) and GW-based compost collected from windrows in the thermophilic phase containing efficient thermophilic microflora. Composting conditions (air circulation, moisture and mixture aeration) were controlled and improved for 22 days (thermophilic and cooling phases), and then the material was kept at ambient temperature for 6 months inside perforated bags for maturation (Bouhia et al. 2020). The biochar used in this study was a commercial product marketed by Noireco Oy, Finland, and obtained via pyrolysis of *Betula pendula* (Betulaceae). The main physicochemical parameters of the biochar and compost are shown in Table 1.

Table 1 Physicochemical properties of the compost, biochar, and biochar-compost mixture

Parameters	Compost	Biochar	Mixture of biochar and compost (1:2)
Moisture ^{a} (%)^{a}	36.07 (0.91)	7.26 (0.01)	27.17 (0.57)
pH_{water} ^{a}	7.97 (0.13)	8.75 (0.09)	8.87 (0.14)
EC (mS/cm)^{a}	5.58 (0.3)	0.4 (0.04)	4.06 (0.23)
TOC (%)^{b}	36.07 (0.91)	51.15 (0.14)	52.33 (0.63)
TKN (%)^{b}	3 (0.02)	0.46 (0.02)	1.56 (0.03)
C/N	12	50	45
P_2O_5 (%) $_{available}$ ^{b}	0.44 (0.02)	0.06 (0.005)	0.30 (0.01)
Exch K% ^{b}	2.24 (0.08)	0.31 (0.04)	1.34 (0.01)
Sulfur% mass	n.d.	0.04	n.d.
Q (gross) Kcal/kg	n.d.	7.562	n.d.
H% mass (MS)	n.d.	3.35	n.d.
Exch Na $^{2+}$% ^{b}	0.317 (0.01)	0.02 (0.004)	0.23 (0.02)
Exch Ca $^{2+}$% ^{b}	1.963 (0.06)	0.98 (0.01)	1.91 (0.04)
Exch Mg^{2+}% ^{b}	0.51 (0.02)	0.12 (0.01)	0.45 (0.02)
Total Cu^{2+} mg/kg ^{b}	32.23 (3.04)	11.99 (3.25)	22.7 (5.8)
Total Mn^{2+} mg/kg ^{b}	189.75 (12.36)	912.81 (83.7)	716.6 (64.4)
Total Fe^{2+} mg/kg ^{b}	4582.26 (209.2)	3739.49 (678.4)	4325.2 (532.6)
Total Zn^{2+} mg/kg ^{b}	155.26 (7.03)	224.28 (0.64)	371.94 (7.7)

^{a} Results are expressed per unit weight fresh matter.

^{b} Results are expressed per unit weight dry matter; TOC: total organic carbon; TKN: total Kjeldahl nitrogen; Exch : exchangeable., Q (gross); gross calorific value, H : hydrogen. The values corresponding to the means (±_standard deviation).

Experimental design

The agronomic trial was conducted between the end of March and the beginning of July 2019 (summer period) under greenhouse conditions at the experimental farm of Mohammed VI Polytechnic University (UM6P) Ben Guerir, Morocco (31.6295° N, 7.9811° W). *Zea mays* was grown in 4 kg pots filled with 3.5 kg of alkaline soil collected from 0-30 cm depth (pH_{water} = 8.29; electrical conductivity (EC) = 0.43 mS/cm; TOC (%) = 1.61; $P_2O_{5(bioavailable)}$ = 19.07 mg kg^{-1}; exchangeable K = 293.05 mg kg^{-1}; exchangeable Ca^{2+} = 8.81 mg kg^{-1}; exchangeable Mg^{2+} = 1285.28 mg kg^{-1}).

The pots were arranged in a completely randomized design with one factor (organic amendment), 5 replicates and 3 treatments: compost-soil [1:10

(v/v)], biochar-soil [1:20 (v/v)], and an equal-ratio biochar-compost combination (BCC). Before planting, homogenous untreated maize seeds (MACHA certified variety) were disinfected with 12% sodium hypochlorite (diluted 1/5), followed by successive washing with sterile distilled water. Pots were checked daily for pest control and nutrient deficiency symptoms and watered solely with distilled water to maintain a moisture level of 60%. Urea (46% N, 180 kg N. ha^{-1}), which was applied before sowing, was the sole fertilizer used during the whole experiment.

Soil chemical properties and plant agrophysiological traits

At the end of the experiment, soil samples were air-dried and passed through a 2-mm sieve before chemical measurements. The pH and electrical conductivity (EC) were measured in an aqueous extract at ambient temperature at a ratio of 1:5 (w/v) following the ISO 10390 (1994) standard. Total organic carbon (%TOC) was measured following organic matter oxidation by potassium dichromate (Amir et al. 2005). Ammonium (N-NH_4^+) and nitrate (N-NO_3^-) were determined using the Kjeldahl distillation method with the addition of Devarda's alloy (Barje et al. 2012). The total Kjeldahl nitrogen (TKN) was assayed in 0.5 g samples by using the classical Kjeldahl procedure according to the AFNOR T90-1110 standard. The available phosphorus (AP) concentration was determined according to Olsen and Sommers (1982) and assayed colorimetrically. The determination of exchangeable cations (K^{2+}, Ca^{2+}, and Mg^{2+}) was performed according to the NF X 31-108 standard. Briefly, cations were extracted using ammonium acetate (1:20 (m/v)) at pH 7, and values were determined using flame spectrometry. Shoot and root biomass were recorded after oven drying at 70°C for 72 h. Prior to drying, root subsamples were taken to assess mycorrhizal colonization and intensity. Multi-elemental trace analysis of previously digested 1 g dried samples (plants and soil) was carried out using ICP-OES (Agilent 5110, Santa Clara, California, USA). The analysed elements were Fe, Zn, Mn, B and Cu. Root density and length were determined in triplicate using a WinRHIZO LA2400 (3RD GEN.) (Regent Instruments Canada Inc).

Chlorophyll fluorescence and plant respiration

The determination of plant chlorophyll fluorescence was carried out in quintuplicate using a portable modulated fluorometer (OS30P$^+$, Opti-Science Instrument, USA). Fluorescence parameters were measured at midday (3500 µmol m^{-2} s^{-1}). A pulse modulated test was used for the measurement of fluorescence levels; (F_0) was the minimal value measured at <0.05 µmol m^{-2} s^{-1} for approximately 1.8 µs. The variable fluorescence of photosystem (F_v) and the maximal fluorescence values (F_m) ratio were measured after applying saturated red-light actinic illumination of 6000 µmol m^{-2} s^{-1} for 0.7 s. Under similar operating conditions, the same leaf's fluorescence equilibrium state (Fe) was recorded after exposure of the plant to ambient light conditions for a period of 40 min. This measurement was made to calculate the maximal quantum efficiency (MQF) using the following equation:

$$MQF = F_v/F_m = (F_m-F_0)/F_m$$

Soil cultivable microbes and plant mycorrhizal traits

The effect of each treatment on soil microbes was assessed through the enumeration of viable cultivable microorganisms (VCMs) on standard solid media (plate count agar). After harvesting, bulk and rhizosphere soil was aseptically recovered from a depth of 0 to 10 cm from the surface of each pot in sterilized bags and stored at 4°C prior to analysis. The sampled soil was first crushed under sterile conditions before preparation of the suspension (1 g soil/10 ml sterilized physiological water), vortexed three times for 5 min to disperse adherent soil particles, serially diluted to 10^{-9} and incubated at 30°C for 48 h. Microbial density was assessed in triplicate and expressed in colony forming units per gram of soil (CFU/g). Similarly, plant-AMF symbiosis was studied after 3 months of plant growth. For each treatment, root subsamples were rinsed under tap water and then cut into 1-2 cm small fragments. To reveal mycorrhizal structures, 50 root fragments were cleared with hot 10% KOH (w/v) and then stained with 0.03% trypan blue (w/v). Furthermore, the colonization percentage was estimated under an optical microscope using the gridline intersection method and based on uniformly dispatching stained root fragments between two 10 cm microscope slides (Giovannetti and Mosse 1980). Mycorrhizal frequency (F%) was determined according to Zhou et al. (2013) and then calculated following the equation:

$$F (\%) = (N-N0) / N \times 100$$

N = number of observed fragments, and $N0$ = number of non-mycorrhizal fragments

Mycorrhizal intensity (M %) was determined following the equation reported by Semane et al. (2017): $M (\%) = (95n5+70n4+30n3+5n2+n1)/N$

where n1, n2, n3, n4 and n5 represent the number of fragments scored 1, 2, 3, 4 and 5, respectively.

Statistical analyses

The results for growth parameters (shoot and root dry weight, number of leaves, and mineral and physico-chemical properties) are the means of five replicates. Data were collected and analysed by one-way ANOVA using SPSS 20. Statistically significant differences between means were determined by the SNK test (Student, Newman, Keuls) at $p < 0.05$. Soil chemical parameters, the nutrient content of plants and their correlation with treatments were subjected to Pearson component analysis using SPSS 20.

Results and discussion

Single and combined application of compost and biochar differentially affect plant aboveground parameters

Most of the studied plant agro-physiological parameters were enhanced due to single and dual application of biochar and compost (Fig. 1A, B). For example, soil amendment significantly improved ($p = 0.05$) shoot length by 10%, 38% and 27% for biochar, compost and BCC, respectively, compared to the control, and the same observation was noted for root length, which was improved by 37%, 57%, and 73% for biochar, compost and BCC, respectively. More importantly, a higher total biomass was obtained in treated soil compared to the control, which was particularly striking when comparing the improvements induced by the 3 treatments, as compost addition improved total biomass by 157%(vs 39.69% and 107% for biochar and BCC, respectively). Likewise, a positive impact on other growth parameters, such as root density, number of leaves and ear production of maize plants was also observed (Table 4), with increases of 28%, 41% and 71%, respectively for compost and 39%, 22% and 43% for BCC. In the case of biochar, root density was the sole parameter that was positively affected (17%, $p = 0.05$), as ear production decreased by 29%, and leaf number was not significantly influenced.

Our results are in line with many literature reports related to the agronomical sustainability and environmental benefits that could be provided by biochar and compost as soil amendments and their role in improving crop productivity (Sorrenti et al. 2012; Abiven et al. 2015). Moreover, different effects on soil properties and plant production would be expected if the two amendments were added separately or combined, as the effect of biochar on low lignin is usually promoted when it is added to stable organic matter such as compost, especially when the compost is rich in nitrogen (Bonanomi et al. 2017; Sorrenti et al. 2017; El-Haddad et al. 2020; Kumari et al. 2020). Similar results were found in the current study, and depending on the treatment, the plant response and modification of soil fertility varied. For example, our findings showed that the best plant productivity was obtained with single application of compost. Therefore, contrary to the hypothesis previously stated, the BCC strategy did not display a synergistic effect, at least on classical plant agronomical parameters. Indeed, when both amendments were combined, plant biomass was reduced by 50% compared to that under compost amendment, which could be attributed to the use of a wood-based biochar, as pyrolysis of such feedstock often generates a product with high adsorption capacity; hence, soil application could induce less availability of plant nutrients, even if nutrient availability remained higher compared to the control (Conversa et al. 2015). The lower biomass yield obtained in the BCC treatment does not necessarily mean that the combination approach is not viable as the most important difference from the compost treatment was the stronger slow-release effect; consequently, we could assume that the beneficial effect of BCC could be more significant in subsequent cropping cycles. However, the resistance of biochar to microbial biodegradation and its long residence time in soil should be taken into consideration, as residual biochar could negatively affect the pool of bioavailable nutrients throughout multiple cropping cycles (Warnock et al. 2007; Verheijen et al. 2010; Gul et al. 2015).

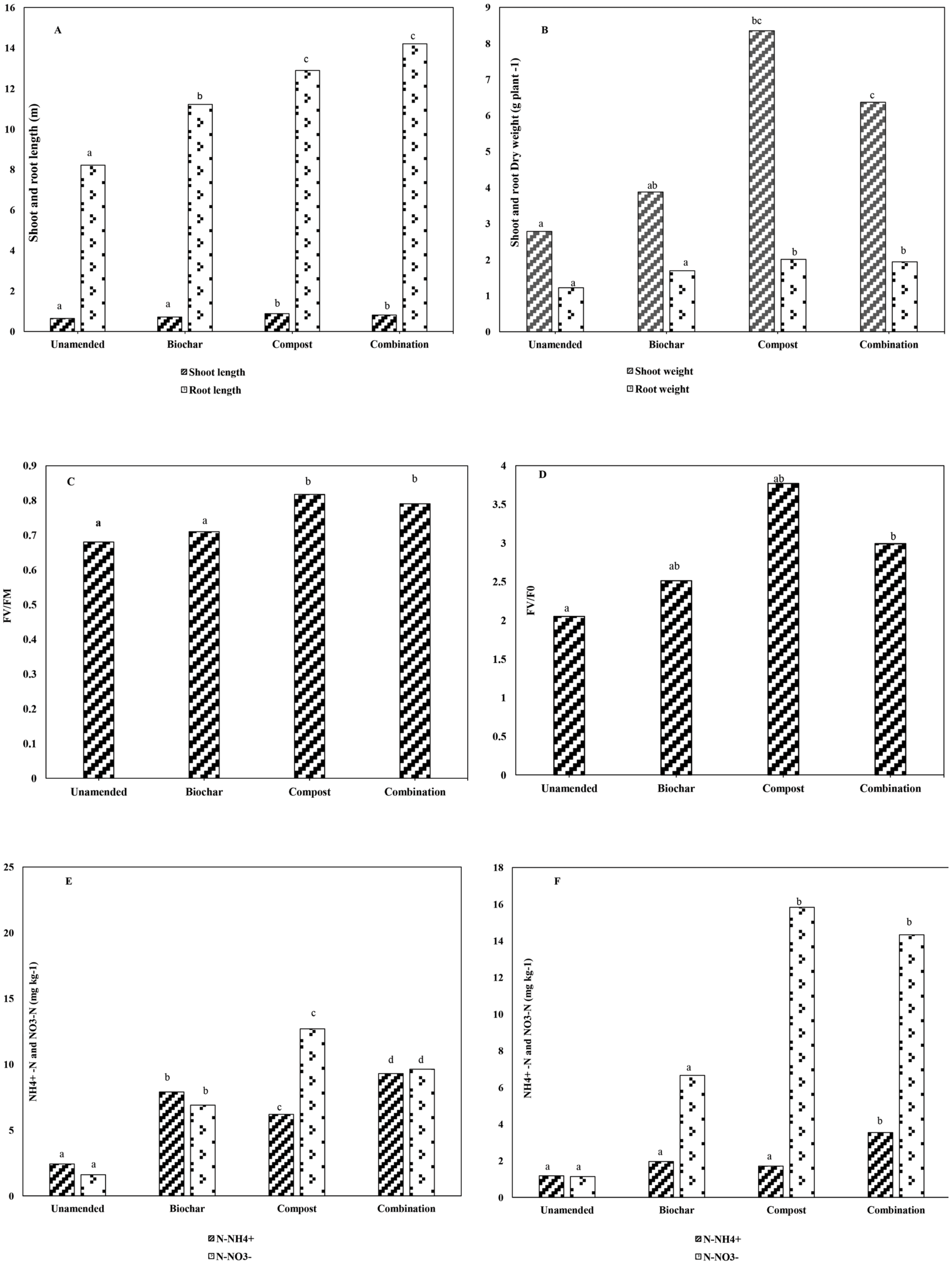

Fig. 1 Effect of biochar, compost and BCC on plant shoot (A) and root dry weight (B), plant photosynthetic parameters (C, D) and soil NH_4^+-N and NO_3^--N after the applications (E) and after harvesting (F)

Bars represent mean values ± SE of five replicates that indicate 95% confidence intervals and columns denoted by a different letter differ significantly at *$p<0.05$*

Regarding the effect of amendments on the photosynthetic rate (Fig. 1C, D), our experiments revealed that chlorophyll fluorescence parameters, maximum quantum efficiency of PSII photochemistry (Fv/Fm), and potential photosynthetic activity (Fv/F0) were higher in plants treated with compost and BCC, with Fv/Fm ratios of 0.817 and 0.79 and Fv/F0 ratios of 3.77 and 2.51, respectively. These values are indicators of healthy plants according to the standards provided by (Maxwell and Johnson 2000). In contrast, biochar application induced less improvement than compost or BCC amendment, with an Fv/Fm ratio of 0.71 (not statistically significant) indicating that the plants were in a stress state.

Single and co-application of biochar and compost strongly affect soil chemistry

Overall, EC, pH, TOC, AP, AK, N-NH_4^+ and N-NO_3^- were significantly affected by the biochar and compost treatments (Table 2, Fig. 1E, F). Initially, the highest pH values were observed after the application of biochar and BCC, while they remained unchanged for the compost and the control treatments (Table 2A). At the beginning of the experiment, EC increased significantly and similarly in all treatments and then decreased after 3 months (Table 2A). With respect to the contents of AP and total phosphorus (TP), the BCC treatment resulted in the highest increases, but %TOC was higher in the biochar treatment (Table 2A). The combined application of organic amendments resulted in the highest increase in soil N-NH_4^+ content, followed by biochar and compost. Additionally, after 3 months, the ammonium content decreased significantly in all treatments except for BCC, which maintained higher values (9 mg.kg^{-1}) (Fig. 1E, F). Regarding N-NO_3^-, the highest soil content was obtained in the compost treatment, followed by the BCC and biochar treatments.

By the end of the experiment, the N-NO_3^- soil content was maintained with biochar treatment and increased significantly for both the compost and BCC treatments. The AP and available potassium (AK) contents increased significantly under the compost and BCC treatments and to a lesser degree with biochar treatment (Table 2A, B). The applied amendments differentially affected soil Ca, Mn, Mg, Fe and Zn (Table 2A, B). For example, soil Mg, Zn and Fe increased by 10%, 91% and 91.6% for BCC and 6%, 92.42% and 86.24% for compost, respectively, compared to the control; however, this difference was not significant in the case of biochar application. Similarly, soil Ca and Mn were not significantly influenced, except for in the compost treatment, where soil available Ca notably increased after 3 months.

The effect or the applied organic amendment on soil fertility and chemistry could be a result of the direct effect of the organic inputs or interactions between physicochemical components. For example, soil pH was highly affected by biochar application, as the initial values, which increased by 0.2 units under biochar treatment and 0.3 units under BCC treatment, further increased at the end of the experiment by 0.3 and 0.5 units, respectively. In contrast, the effect of compost on soil pH was negligible during the whole experiment. In this regard, several investigations have reported that biochar and the co-application of biochar and compost induce an increase in soil pH, which is attributed to the higher content of nutrients, particularly cations, which increases soil salinity (Gundale and DeLuca 2006; Gusiatin and Kulikowska 2016; Sigua et al. 2016). In addition, the increase in pH could be related to negatively charged functional groups on the biochar surface, including carboxylic acids (-COOH), hydroxyl (-OH) groups, small alkyl chains such as methane groups (-CH_3) and phenols that combine with protons (H^+) in soil, inducing an increase in soil pH (Gul et al. 2015). Additionally, the reduction in N-NH_4^+ content due to the nitrification process induces a slight increase in nitrite content (Fig. 1B) and leads to a direct increase in pH value (Matsuyama et al. 2005). It has been proven that wood-derived biochar has the ability to retain N-NH_4^+ from the soil through surface chemisorption (Wang et al. 2015). This retention was confirmed by the strong correlation between soil pH, TOC (%) and N-NH_4^+, with $p = 0.977$ and $p = 0.862$, respectively (Table 5). The initial EC values (Table 2A, B) increased significantly compared to those in untreated soil from 0.41 to 1.86 ms cm^{-1}, 3.02 ms cm^{-1}, and 2.02 ms cm^{-1} for biochar, compost and BCC, respectively. At the end of the experiment, the EC values decreased in all treatments, and similar trends were observed for soil TOC content, which is in agreement with previous studies reporting the stabilization of the EC value over time (Bonanomi et al. 2017; Tsai and Chang 2019). According to the same studies, such evolution could be the result of the richness of organic amendments in terms of alkaline metals (K^+, Ca^{2+} and Mg^{2+}), especially in compost (Table 1). Notably, the final EC value in BCC was significantly lower than that

Table 2 Effect of single and dual application of compost and biochar on soil chemical composition at the beginning of the experiment (A) and after harvesting (B)

A) Amendment T=0 days	pH_{water}	EC (mS/cm)	TOC (%)	$P_{assimilable}$ mg/Kg	Exch K^{2+} mg/kg	Mn mg/kg	Exch Ca^{2+} g/kg	Exch Mg^{2+} mg/kg	Fe mg/kg	Zn mg/kg	TP (P_2O_5) mg/Kg
Unamended	8.19 (0.01) ^{a}	0.41 (0.05) ^{b}	1.28 (0.07) ^{a}	22.33 (0.9) ^{a}	300.5 (14) ^{a}	8.89 (0.1) ^{a}	8.01 (0.8) ^{a}	1128 (47) ^{a}	6.56 (0.1) ^{a}	0.71 (0.04) ^{a}	363.26 (8.5) ^{a}
Biochar	8.34 (0.01) ^{b}	1.86 (0.1) ^{a}	3.66 (0.14) ^{c}	41.67 (3.1) ^{a}	392.9 (12) ^{b}	7.1 (0.08) ^{a}	7.44 (3.1) ^{a}	1155.5 (6) ^{a}	8.24 (0.2) ^{a}	2.21 (0.07) ^{a}	432.05(1.1) ^{b}
Compost	8.14 (0.01) ^{a}	3.02 (0.1) ^{a}	2.27 (0.17) ^{b}	159.3 (22) ^{b}	1287.2 (42) ^{c}	16.6 (1.6) ^{b}	7.32 (7.1) ^{a}	1188.1 (63) ^{a}	86.5 (4.7) ^{b}	5.16 (1.3) ^{b}	464.05 (2.7) ^{c}
BCC	8.51 (0.03) ^{c}	2.02 (0.3) ^{c}	5.27 (0.08) ^{d}	246.67 (8.2) ^{c}	1112.7 (21) ^{c}	16.6 (0.6) ^{b}	8.05 (2.1) ^{a}	1245.7 (35) ^{a}	76.5 (0.9) ^{c}	8.41 (0.4) ^{c}	483.5 (3.4) ^{d}
Significance	**	**	**	**	**	**	NS	NS	**	**	**

B) Amendment T= 3 months	pH_{water}	EC (mS/cm)	TOC (%)	$P_{assimilable}$ mg/Kg	ExchK^{2+} mg/kg	Mn mg/kg	Exch Ca^{2+} g/kg	Exch Mg^{2+} mg/kg	Fe mg/kg	Zn mg/kg	TP (P_2O_5) mg/Kg
Unamended	8.18 (0.03) ^{a}	0.43 (0.06) ^{a}	1.06 (0.02) ^{a}	19.33 (1.11) ^{a}	224.12 (16) ^{a}	4.11 (0.1) ^{a}	5.62 (0.2) ^{a}	668.32 (38) ^{a}	7.28 (0.2) ^{a}	0.42 (0.07) ^{a}	320.78 (14.2) ^{a}
Biochar	8.48 (0.01) ^{c}	1.44 (0.06) ^{c}	3.18 (0.4) ^{b}	27.33 (2.44) ^{a}	325.9 (9.5) ^{a}	11 (1.1) ^{b}	4.88 (0.2) ^{a}	692.4 (36) ^{a}	7.30 (0.2) ^{a}	1.72 (0.04) ^{b}	367.5 (3.3) ^{b}
Compost	8.24 (0.02) ^{b}	1.35 (0.1) ^{c}	1.92 (0.16) ^{c}	362.67 (25.1) ^{b}	2927 (57.) ^{b}	7.31 (0.1) ^{b}	8.92 (0.5) ^{b}	857.8 (37) ^{b}	16.34 (0.7) ^{b}	3.68 (0.48) ^{c}	406.9 (10.8) ^{c}
BCC	8.66 (0.01) ^{d}	1.05 (0.01) ^{b}	4.08 (0.08) ^{d}	329.33 (17.7) ^{b}	1484.4 (54) ^{c}	7.24 (0.2) ^{c}	5.24 (0.2) ^{a}	1117.9 (39) ^{c}	22.71 (0.2) ^{c}	5.26 (0.2) ^{d}	448.52 (2.01) ^{d}
Significance	**	**	**	**	**	**	**	**	**	**	**

Results represent means (±_standard deviation) of five replicates. Data within the same column followed by different letters are significantly different according to the Student, Newman–Keuls test at $p < 0.05$. Symbols: $*P<0.05$. $**P<0.01$, $***P<0.001$.

in its compost counterpart, which may plausibly be due to nutrient adsorption by the biochar fraction, thus reducing the nutrient concentrations in soil solution and leachates (DeLuca et al. 2015), although this effect was not observed for the biochar treatment, suggesting that other mechanisms could be involved. Indeed, another study suggested that EC reduction can also be associated with microbial assimilation of SO_4^{2-} and $N\text{-}NO_3^-$ following the biodegradation of organic matter (Arif et al. 2018). In addition, alkaline soil conditions (pH > 7.5) favour Ca-P precipitation reactions, resulting in a sequence of products that could generate a direct effect on soil pH and phosphorus solubility (Gundale and DeLuca 2006; Sigua et al. 2016). This effect was clearly highlighted in our study (Table 2B), as the content of Ca^{2+} in the compost-amended soil was significantly higher than that in the BCC-amended soil. Ultimately, the drastic decrease in soil concentrations of ions such as Mn, Mg, Fe and Zn (Table 2A, B) could be the result of the combinatory effect of plant nutrient uptake and microbial activity.

Humic substances contained in compost are its main organic carbon reservoir. Organic compounds in compost are less difficult to degrade (Gusiatin and Kulikowska 2016) than those existing in biochar, which is characterized by a high C/N ratio, resulting in high resistance when added to soil. Moreover, the ability to promote the polymerization of small organic molecules already exists on the surface of soil particles (Song et al. 2019). Several studies also found that biochar and the simultaneous application of biochar-compost can increase and maintain a high percentage of TOC in soil compared to that under compost application alone (Gao et al. 2017; Tang et al. 2020).

According to our study, the soil AP content increased significantly at the end of the experiment due to the amendments, increasing from 159.3 mg/kg and 246.67 mg/kg to 362.67 and 329.33 for compost and BCC, respectively (Table 2A, B). Moreover, the AP value remained low and not significant for biochar. Similarly, the results showed that AK increased by 328% and 270% for compost and BCC, respectively, and continued to increase to 127% for compost and 33.40% for BCC, hence demonstrating the ability of the added biochar to absorb nutrients and slow nutrient release. In addition, the correlation study (Table 5) showed that soil EC was strongly correlated ($p < 0.001$) with soil AP ($p = 0.948$) and AK ($p = 0.978$). Furthermore, for all amendments, a significant improvement in soil total phosphorus (TP) was observed initially compared to the control, with values of 19%, 28% and 33% for biochar, compost, and BCC, respectively; however, after harvesting, the TP values slightly decreased by 14.94%, 12.33% and 7.24%, respectively, which explains the increase in AP concentration by the end of the experiment. These results are in agreement with other research findings showing that the primary factors determining P mineralization are related to the plant rooting system as well as the microbial biomass, given that soil microorganisms can produce a diversity of extracellular enzymes (ex, phytase, phosphatase, and phospholipase) with P hydrolysis properties (Novak et al. 2013). Findings by Masto et al. (2013) show that biochar produced from *Eichornia crassipes* could greatly enhance microbial P mineralization (by 3-fold compared to the control) and increase phosphatase activity by almost 20% after only 20 days of culture. Moreover, many studies have shown that biochar produced at relatively low temperatures can further enhance P availability compared to that obtained with biochar produced at high pyrolysis temperatures (Hale et al. 2015; Xu et al. 2016). In addition, properties such as surface area and O:C play the same role as organo-mineral complexes and are expected to increase nutrient retention in biochar-amended soil, especially for negatively charged ions such as $H_2PO_{4^-}/HPO_4^{2-}$ and low-molecular-weight DOC (Chandra et al. 2008; Lu et al. 2014; Prommer et al. 2014). Many studies have shown that biochar-based lignocellulosic waste such as wood is relatively poor in nutrients and characterized by a high sorption capacity for low-molecular-weight substances, causing low colonization of microorganisms within and on biochar surfaces in soil (Bird et al. 2011; Novak et al. 2013; Quilliam et al. 2013).

Single application of compost and BCC affect positively plant nutrient uptake

The effect of single or combined organic amendments on soil and plant nutrient content was studied. The obtained results (Table 3) showed that biochar had no significant effect on shoot NPK content; however, compost and BCC treatment significantly improved shoot NPK content compared to the control. Indeed, compost application enhanced the shoot-N, shoot-P and shoot-K contents by 42%, 58%, and 63%, respectively. A lower improvement was observed with BCC than with compost, as shoot-N, shoot-P and shoot-K increased by 38%, 41% and 40%, respectively. Notably,

Table 3 Effect of single and dual application of compost and biochar on plant shoot nutrient content

Amendment	TKN (%)	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B
		Elements%				mg Kg^{-1} DM				
Unamended	0.73 (0.07) ^{a}	0.12 (0.01) ^{a}	2.45 (0.2) ^{a}	1.11 (0.05) ^{b}	0.42 (0.04) ^{a}	323.59 (17.7) ^{a}	92.61 (4.7) ^{a}	4.31 (0.4) ^{a}	28.3 (0.7) ^{a}	31.8 (1.2) ^{a}
Biochar	0.67 (0.005) ^{a}	0.11 (0.01) ^{a}	2.69 (0.2) ^{a}	1.12 (0.1) ^{b}	0.52 (0.08) ^{ab}	322.19 (35.1) ^{a}	94.36 (1.05) ^{a}	4.34 (0.2) ^{a}	31.52 (2.9) ^{a}	38.6 (0.6) ^{b}
Compost	1.04 (0.01) ^{b}	0.19 (0.01) ^{a}	3.99 (0.3) ^{b}	0.66 (0.06) ^{a}	0.58 (0.03) ^{ab}	350.72 (10.8) ^{a}	96.36 (1.2) ^{a}	6.11(0.05) ^{b}	40.01 (3.6) ^{a}	48.3 (1.2) ^{c}
BCC	1.01 (0.02) ^{b}	0.17(0.01) ^{b}	3.44 (0.2) ^{b}	0.72 (0.14) ^{a}	0.70 (0.06) ^{b}	386.91 (14.5) ^{a}	95.09 (1.6) ^{a}	5.24 (0.41) ^{a}	37.54 (5.3) ^{a}	43.9 (0.8) ^{d}
Signifiance	***	***		*	**	ns	**	**	ns	***

Results represent means (±_standard deviation) of five replicates. Data within the same column followed by different letters are significantly different according to the Student, Newman–Keuls test at $p < 0.05$. *$P<0.05$. **$P<0.01$, ***$P<0.001$.

opposite trends were observed for shoot Ca^{2+} content, as it significantly decreased following the application of compost (-68%) and BCC (-54%) and maintained a similar value compared to the control when biochar was solely used. Moreover, shoot-Mg and shoot-B significantly improved for all treatments compared to the control. Shoot-Mg increased by 24%, 38% and 66%, and shoot-B increased by 21%, 52% and 38% for biochar, compost and BCC, respectively. Moreover, improvement of shoot-Cu (22%) was only observed in the compost treatment, and shoot Fe, Mn and Zn contents were not significantly affected by single or combined application of both amendments.

According to Conversa et al. (2015), shoot P and K contents were adequate in both the BCC and compost treatments, which was particularly striking in the case of K, as the value increased from 24 g.kg^{-1} (control) to almost 34 g.kg^{-1} for BCC and 39 g.kg^{-1} for compost. On the other hand, biochar did not improve the shoot P content, which may be related to the high pH value and the small microsites of biochar (compared to roots) that may prevent adequate P assimilation (Hammer et al. 2014). On a different note, our findings show that plant belowground traits were positively affected by single and co-application of both amendments, as root growth and density were improved significantly using biochar and compost compared to the control, which could be plausibly attributed to a better nutrition and the bio-stimulatory effect of compost (Baldi et al. 2010). Similarly, Abiven et al. (2015) reported that biochar application induced the modification of root architecture and improved the growth and density of maize rooting systems. The root density was considerably developed in all treatments after the addition of biochar even if lesser nutrient uptake was recorded compared to single application of compost, regarding shoot-P, shoot-Mg and shoot-B showed (Table 3). In fact, according to several reports investigating the effect of biochar on root architecture (Emami et al 2019; Batool and Iqbal 2019; Messina et al. 2020), the lower rhizosphere available P fraction usually induce a higher development of the rooting system, but all the roots are not always functional, hence resulting in less nutrient uptake.

Biochar application negatively affects plant AMF traits and soil VCM

The assessment of plant mycorrhizal traits showed that the highest mycorrhizal frequency (>90%) was obtained in the BCC and the control treatments (Table 4), followed by biochar (66.6%) and compost, where the mycorrhizal frequency (22%) dramatically decreased compared to the control. In contrast, mycorrhizal intensity was negatively affected by all organic amendments, as it was reduced by 56%, 91.6%, and 99% for compost, BCC and biochar, respectively. On another note, enumeration of VCM (Table 4) showed that there was strong variation between treatments, although it was not statistically significant. For example, according to PCA, the compost treatment revealed the highest viable microbial biomass compared to the control (3.94 x 10^8 CFU g^{-1}) as it accounted for 8.65 x 10^9 CFU g^{-1}, followed by BCC (8.2 x 10^7 CFU g^{-1}), then biochar (1.71 x 10^8 CFU g^{-1}).

AMFs are obligate biotrophs and are a critical component for the good functioning of most agrosystems. AMFs are highly specialized in P acquisition and are known for their ability to alleviate plant water stress under water deficiency conditions by developing extraradical hyphae that can access microsites of water and nutrients within small soil pores that are unreachable by plant roots (Ruth et al. 2011; Ruiz-Lozano et al. 2012). Biochar porosity varies enormously, affecting its ability to improve nutrients and its water availability, depending on the feedstock and pyrolysis conditions (Jeong et al. 2015).

Many studies have found that biochar can promote mycorrhizal colonization of plant hosts and enhance phosphorus solubilization (Atkinson et al.

Table 4 Effect of single and dual application of compost and biochar on mycorrhizal frequency (%F), mycorrhizal intensity (%M), viable cultivable microorganisms, and plant growth parameters

	Parameters					
	Mycorrhizal frequency (%)	Intensity of mycorrhizal colonization (%)	Total microflora CFU/ml	Root density (m^2)	Leaf number/plant	Ear number/plant
Unamended	100 ^{c}	83.3 (11.11) ^{d}	3.9 x $10^{8\ a}$	0.138 (0.008) ^{a}	6.75 (0.375) ^{a}	1.75 (0.75) ^{ab}
Biochar	66.6 (11.) ^{b}	0.66 (0.04) ^{a}	1.7 x $10^{8\ a}$	0.1621 (0.004) ^{c}	6.75 (0.75) ^{a}	1.25 (0.37) ^{a}
Compost	22.21 (7.4) ^{a}	7 (4) ^{a}	8.6 x $10^{9\ a}$	0.178 (0.004) ^{c}	9.5 (1) ^{b}	3 (0.5) ^{b}
BCC	94.4 (7.4) ^{c}	36.6 (17.7) ^{b}	8.2 x $10^{7\ a}$	0.1915 (0.001) ^{b}	8.25 (0.75) ^{ab}	2.5 (0.5) ^{ab}
Significance	**	**	NS	**	*	*

Results represent means (±_standard deviation) of three replicates. Data within the same column followed by different letters are significantly different according to the Student–Newman–Keuls test at $p < 0.05$. Symbols: *$P<0.05$. **$P<0.01$, ***$P<0.001$.

2010; Blackwell et al. 2010; Ruiz-Lozano et al. 2012); however, our findings proved otherwise, as plant mycorrhizal parameters were negatively affected following biochar application, which can be related to the biochar nature as well as the applied quantity. Indeed, Conversa et al. (2015) showed that the application of a wood tree-based biochar (*Abies alba)* significantly reduced mycorrhizal frequency, although the colonization percentage was not affected. Likewise, the quantity of applied biochar is an important factor, as depending on this value, later mycorrhizal colonization can be either enhanced or reduced (Warnock et al. 2010; Hale et al. 2013; Mukherjee and Zimmerman 2013). Pyrolysis temperature is also important, and some studies showed that biochar produced at a high temperature (more than 700°C) could inhibit the communication between soil gram-negative bacteria by 10 times more than biochar produced at 300°C by interrupting the quorum sensing allowing recognition between microorganisms and plants (Masiello et al. 2013).

Soil microorganisms can enhance plant nutrient use efficiency, although they are directly influenced by nutrient quality and the type of organic amendment, which determine microbial diversity, abundancy and activity (Chan et al. 2008; Gul et al. 2015; Escobar et al. 2020). For example, biochar application induces a significant modification of soil porosity and its chemical properties under high EC, thus impacting microbial activity (Quilliam et al. 2013; Jaafar et al. 2014). In this context, several studies have shown that biochar could play an important role in controlling microbial growth due to its high adsorption capacity with regard to organic compounds such as phenols. Furthermore, under alkaline conditions, biochar is more suitable for gram-positive bacteria, as they can use various complex carbon structures, as opposed to gram-negative bacteria, which can use limited and preferential compounds (Deenik et al. 2010; Farrell et al. 2013). Other findings suggested that the low nutrient contents of wood-based biochar could induce lower microbial colonization and damage the fertility of poor soils, as nutrients and water from soil solution are often retained and stored in mesopores (<50 nm), which remain inaccessible for microorganisms and plants (Masto et al. 2013; Quilliam et al. 2013; Gul et al. 2015). Notably, the high adsorption/desorption ability of biochar surfaces can negatively affect several enzymatic reactions, which slows the decomposition of organic matter and nutrients (Bailey et al. 2011; Burns et al. 2013). In fact, high biochar porosity can reduce extracellular enzymes by interfering with substrate diffusion by functional groups of biochar on the active sites of enzyme catalysis. Indeed, the activities of several enzymes (alkaline phosphatase, β-glucosidase, invertase and protease) that are enhanced by compost application are inhibited by biochar (Lammirato et al. 2011; Tang et al. 2020).

Correlations between plant agrophysiological traits and soil fertility parameters

The correlation analyses (Table 5) showed a significant correlation ($p < 0.001$) between soil EC and plant phosphorus assimilation ($p = 0.925$). More importantly, the N:P ratio of unamended soil (mean of 6) was modified under the BCC and compost treatments (N:P = 5). In contrast, this value remained unchanged following single biochar application. N and P concentrations are regulated during photosynthesis, and the N:P ratio can provide valuable information regarding the dynamics of plant growth (Güsewell 2004). In our experiment, the observed nitrogen and phosphorus deficiencies in the biochar treatment could be related to photosynthesis inadequacy, which disrupts proper functioning of the Calvin cycle, thus limiting nutrient supply to chloroplasts (Lima et al. 1999). Moreover, the increase in K content of the maize plants in BCC- and compost-amended soil confirms the rich exchangeable K concentration (Sorrenti et al. 2016). Interestingly, the increases in shoot P and K contents reduced the uptake of other nutrients, such as Ca^{2+} and Mn^{2+}, which could be related to the antagonistic effect between ions. Indeed, the variation in shoot Ca in relation to shoot K and shoot Mg (Table 5) revealed clear negative correlations of $p = -0.827$ and $p = -0.630$, respectively.

Conclusion

In this study, we assessed in a short-term experiment the effect of single and dual application of wood-based biochar and compost generated from OMWS processing on maize agrophysiological parameters and some soil chemical and microbial traits. Biochar addition singly or in BBC significantly increased the soil TOC, EC, and pH. Furthermore, adding biochar to compost increased the levels of macro- and micronutrients compared to those under single application of biochar. The soil fertility and its nutrient holding capacity improved significantly with regard to available phosphorus and

Table 5 Correlation coefficients of soil parameters: pH; EC; AP, available phosphorus; AK, available potassium; Ca; Mg; Zn; TP, total phosphorus; NH^+_4 nitrogen; NO_3^- nitrogen; plant assimilable P, phosphorus; plant assimilable K, potassium; Zn, zinc; Mg, magnesium; and Ca, calcium

Character	SoilpH	SoilEC	AP	AK	SoilCa	SoilMg	Soiltp	SoilTOC	PlantP	PlantK	SoilNH4	SoilNO3	SoilZN	PlantZn	PlantMg	PlantCa
SoilpH	1.000	0.909^{NS}	0.413^{NS}	0.942^{NS}	0.518^{NS}	0.665**	0.693^{**}	0.977***	0.086^{NS}	0.695^{NS}	0.862***	0.372^{NS}	0.651*	0.234^{NS}	0.617^{*}	-0.197^{NS}
SoilEC		1.000	0.948***	0.978***	0.770**	0.605*	0.713**	0.142^{NS}	0.975***	0.925**	0.291^{NS}	0.836**	0.747**	0.718**	0.50^{NS}	0.891***
AP			1.000	0.948***	0.594*	0.799**	0.830**	0.358^{NS}	0.946***	0.851***	0.052^{NS}	0.858***	0.876***	0.746**	0.645*	0.879***
AK				1.000	0.806**	0.601*	0.704*	0.149^{NS}	0.957***	0.916***	0.268^{NS}	0.827**	0.746**	0.761**	0.520^{NS}	-0.845**
SoilCa					1.000	0.085^{NS}	0.215^{NS}	-0.398	0.747**	0.744**	-0.288^{NS}	0.468^{NS}	0.265^{NS}	0.567*	0.062^{NS}	-0.528^{NS}
SoilMg						1.000	0.880***	0.685*	0.675*	0.564^{NS}	0.791**	0.641*	0.925***	0.639*	0.747**	-0.623*
Soiltp							1.000	0.750**	0.744**	0.754**	0.807**	0.813**	0.79***	0.673*	0.824**	-0.748**
SoilTOC								1.000	0.171^{NS}	0.237^{NS}	0.861***	0.492^{NS}	0.705*	0.308^{NS}	0.690*	-0.283^{NS}
PlantP									1.000	0.917***	0.317^{NS}	0.775**	0.790**	0.762**	0.502^{NS}	-0.823**
PlantK										1.000	0.309^{NS}	0.784**	0.755**	0.719**	0.518^{NS}	-0.827**
SoilNH4											1.000	0.591*	0.795**	0.311^{NS}	0.768**	-0.538^{NS}
SoilNO3												1.000	0.827**	0.716**	0.661*	0.856***
SoilZN													1.000	0.744**	0.783**	-0.760**
PlantZn														1.000	0.325^{NS}	0.501^{NS}
PlantMg															1.000	-0.630*
PlantCa																1.000

*$P<0.05$ **$P<0.01$ ***$P<0.001$.

potassium, Mg^{2+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, NH_4^+-N and NO_3^--N, with a negative impact on exchangeable Ca^{2+} after 3 months of experiments. Nevertheless, single application of biochar had a negative impact on mycorrhizal symbiosis; however, this impact was not statistically significant for soil VCM. Overall, single application of compost gave the best results in terms of plant growth and soil fertility improvement; thus, a synergistic effect of both amendments was not observed, which could be due to the applied rate of biochar and the duration of the experiment. In this context, we suggest that the assessment of such dual strategies should cover more than one cropping cycle and that the biochar rate should be less than 5%.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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