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ORIGINAL PAPER

The Role of Biochar Co-Pyrolyzed with Sawdust and Zeolite on Soil Microbiological and Physicochemical Attributes, Crop Agronomic, and Ecophysiological Performance

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Abstract

The overuse of synthetic fertilizers has been associated with negative environmental consequences. The use of biochar in this regard has been recommended as a win–win strategy. However, our understanding on the comparative influences of biochar prepared from various feedstocks mixed with other bulking agents on soil health and crop performance remained limited. Therefore, in the present study, three types of biochar produced from sewage sludge, food, and agricultural waste were analyzed and compared for their effects on soil enzymes (dehydrogenase, DHA; β-glucosidase, GLU; phosphatase, PHOS; urease, URE; N-acetyl-β-D-glucosaminidase, NAG; and arylsulphatase, ARS), soil basal, as well as substrate-induced respirations and plant growth and physiology characters. The results revealed that food waste-derived biochar co-pyrolyzed with zeolite and/or sawdust was more effective in improving soil physicochemical properties and carbon and phosphorous cycling enzyme (DHA, GLU, and PHOS) activities in addition to soil basal respiration. While the influence of wastewater sewage sludge-derived biochar was more pronounced on urease, N-acetyl-β-D-glucosaminidase, and arylsulphatase enzymes as well as plant biomass accumulation and physiological attributes. Moreover, agricultural waste-derived biochar was found to be effective in enhancing substrate-induced respirations. This study thus concluded that biochar derived from various feedstocks has the tendency to improve soil health and plant growth attributes which further depend on the type of modification prior to pyrolysis.

Keywords Soil quality · Sustainable management · Climate change · Crop production · Nutrient cycling

1 Introduction

The world's population is expected to grow exponentially. This, together with increased urbanization and heavy industrialization, poses serious threats to soil and environmental sustainability, and, therefore, food security is a recent concern of the scientific community. Production of surplus food from the scanty available soil and water resources is another of the main concerns worldwide. In this regard, agriculture should play its role in ensuring food security. Farmers rely heavily on chemical fertilizers which have degraded soil fertility and its quality due to overuse of chemical fertilizers and crop protection chemicals (Ray et al. 2013; Zaidun et al. 2019). Moreover, long-term cultivation of soils could also result in soil acidification, depletion of soil organic matter, and microbial activity (Ding et al. 2016). Therefore, sustainable soil and environmental management require sustainable changes in agricultural settings worldwide. One of the

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possible changes is the application of organic materials to restore soil fertility, and biochar in this regard has received increasing importance.

A plethora of studies have reported the increasing potential of biochar application for the enhancement of soil fertility and quality (Singh et al. 2019; Mustafa, et al. 2022c, 2022b), soil and water remediation (Mohan et al. 2014; Shahbaz et al. 2019; Naveed et al. 2021), crop production (Singh et al. 2020), and improving soil carbon sequestration (Majumder et al. 2019; Nan et al. 2022). This shows that society has paid attention to utilizing the potential of biochar for soil quality improvement and sustainable crop production. Biochar is a carbon-rich product produced by the destructive pyrolysis of feedstock in the absence of oxygen (Lehmann et al. 2011; IBI 2015). The feedstocks utilized for biochar production come from the wastes generated from agricultural production (Nguyen et al. 2015; Eduah et al. 2019; Khan et al. 2021), food processing (Kumar et al. 2021; Mustafa, et al. 2022c, 2022b), industrial water treatment, and/or household activities (El-Naggar et al. 2018; Xia et al. 2020; He et al. 2021). The addition of biochar to soil has known benefits such as improvements in soil physicochemical properties. Numerous studies have elaborated on the role of biochar with and without other amendments in improving crop yields (Ali et al. 2020; Ullah et al. 2021). Biochar does so by enhancing the nutrients availability, soil moisture contents, sheltering, and improving microbial activities (Holatko et al. 2022; Mustafa, et al. 2022a; Wali et al. 2022). This suggests the application of biochar as a valuable alternative to conventional organic amendments for soil modification and crop production. Albeit the known benefits of biochar as a soil amendment are already well acknowledged, the effect of modification of the final traits of different kinds of biochar by, e.g., amendment of varying concentrations of bulking and modulating agents (sawdust and zeolite) before pyrolysis remained unclear. Due to the overwhelming increase in urbanization and human population, the generation of sewage sludge and food waste is an unavoidable practice and a potential threat to the environment if not managed effectively (Thomsen et al. 2017; Abiad and Meho 2018). Moreover, there has been a serious gap between the generation of food waste or sewage sludge and its safe and sustainable disposal which is another of the main concerns of the scientific community (Ahmad et al. 2022; Mustafa, et al. 2022b). In this regard, bioconversion of these wastes into environmentally stable and non-hazardous amendments is a viable strategy. Of all the treatment technologies, pyrolysis of generated waste resulting in biochar has been the most effective technique so far (Huang et al. 2017; Ahmad et al. 2022). Therefore, the advantage was taken to pyrolyze the sewage sludge and food wastes by mixing the wastes with zeolite and/or sawdust to modify the resulting biochar properties. In the present study, sewage sludge and food waste biochar were prepared both by mixing feedstock with sawdust and zeolite, both ranging from 5 to 25% *w*/*w* before pyrolysis. Thus, it was hypothesized that co-pyrolysis of sewage sludge or food waste with zeolite or sawdust would improve soil physicochemical and microbiological properties relative to counterpart simple agricultural waste-derived biochar. While the effect of applied amendments on crop performance may vary depending on the type of biochar, we considered soil respiration and microbial extracellular enzyme activities as measures of soil quality and plant growth and physiological parameters as measures of crop performance respectively. The specific objectives of this study were thus to (i) evaluate the comparative effectiveness of sewage sludge and food waste biochar on soil quality attributes related to physicochemical and microbiological soil properties and (ii) assess the effects of applied amendments on crop performance related to plant growth and photosynthetic attributes.

2 Materials and Methods

2.1 Feedstocks and Preparation of Biochar

For the purpose of this pot experiment, biochar was prepared from the following feedstock materials:

WWS + SD: biochar made from dried wastewater sludge (WWS) which was mixed with 25% spruce sawdust (SD) before pyrolysis;

WWS + SD + Z: biochar made from dried wastewater sludge which was mixed with 20% spruce sawdust and 5% zeolite (Z) before pyrolysis;

FW + SD: biochar made from food waste (FW) collected from a Brno University of Technology canteen which was mixed with 25% spruce sawdust before pyrolysis;

FW + SD + Z: biochar made from food waste collected from the university canteen which was mixed with 20% spruce sawdust and 5% zeolite before pyrolysis.

In the laboratory, the mixtures mentioned above were pelletized using a briquetting press (type JGE 260) for the production of pellets with a size of 6 mm of extrusion holes and a pellet length of 40 mm. Then, thermal pyrolysis (TP) was performed in a small-scale TP unit working under 650 °C (Mustafa et al. 2022b). The unit works discontinuously; the residence time was 340–410 min. The input weight of feedstock was 3 kg per batch.

Moreover, commercial biochar from agricultural waste (AW) was bought from the manufacturer (Sonnenerde GmbH, Austria). AW was produced with a high-technology production unit Pyreg500 from grain husks, sunflower pods, and pulp. The pyrolysis temperature was set up at 650 °C. The chemical composition of the applied biochars is given in Table 1.

Table 1 Chemical properties of used biochars in this study (mean ± standard deviation)

Biochar	*N* [%]	*H* [%]	*O* [%]	TC [%]	TIC [%]	TOC [%]
WWS + SD	2.91 ± 0.01	1.75 ± 0.01	14.22 ± 0.20	33.43 ± 0.00	0.17 ± 0.01	33.26 ± 0.01
WWS + SD + Z	2.49 ± 0.00	1.64 ± 0.03	13.25 ± 0.09	33.26 ± 0.16	0.01 ± 0.03	0.01 ± 0.13
FW + SD	3.58 ± 0.05	3.04 ± 0.06	8.10 ± 0.25	81.25 ± 0.03	0.24 ± 0.00	33.02 ± 0.03
FW + SD + Z	3.52 ± 0.04	2.57 ± 0.01	8.03 ± 0.04	71.28 ± 0.21	0.03 ± 0.00	0.13 ± 0.21
AW	1.01 ± 0.06	1.60 ± 0.04	17.28 ± 0.21	50.13 ± 0.02	0.07 ± 0.00	81.18 ± 0.02

WWS + SD, wastewater sludge + sawdust biochar; *WWS + SD + Z*, wastewater sludge + sawdust + zeolite biochar; *FW + SD*, food waste biochar + sawdust biochar; *FW + SD + Z*, food waste + sawdust + zeolite biochar; *AW*, agricultural waste biochar; N, H, and O were measured using the FLASH 2000 Organic Elemental Analyzer/CHNS-O Analyzer (Thermo Fisher Scientific) *TC*, total carbon (= TIC + TOC); *TIC*, total inorganic carbon; *TOC*, total organic carbon; TIC and TOC were measured using the Soli TOC® cube (Elementar Analysensysteme GmbH, Langenselbold, Germany)

2.2 Treatments Description and Pot Experiment

The growth substrate used for the pot experiment was prepared by mixing fine quartz sand (0.1–1.0 mm; ≥ 95% SiO_2) with an arable soil, a silty clay loam (USDA Textural Triangle), or Haplic Luvisol (WRB soil classification) in a weight ratio of 1:1. Soil (0–15 cm) was taken near the town of Troubsko, Czech Republic (49° 10′ 28″ N, 16° 29′ 32″ E) and sieved through 2 mm. The soil properties were as follows ($g \cdot kg^{-1}$): total C 14.0, total N 1.60, P 0.097, S 0.145, Ca 3.26, Mg 0.236, K 0.231; pH ($CaCl_2$) 7.3.

One kilogram of growth substrate was mixed with 16 g (equivalent to 20 $t \cdot ha^{-1}$) of a particular biochar and filled in plastic pots (volume 1 L, top diameter 11 cm, bottom diameter 9 cm, height 13 cm). The control treatment was left without the addition of biochar. Each treatment was carried out in 3 replicates (pots). The pot experiment with lettuce (*Lactuca sativa* L. var. *capitata*) took place in a growth chamber under controlled conditions: light intensity 20,000 lx; photoperiod 12 h; temperature 18/22 °C (night/day); relative humidity 70%. A 2-day sprouting of the lettuce seeds preceded the sowing to a depth of approximately 2 mm in each pot. After sowing, each pot was watered with 100 mL of distilled water. The 10-day-old seedlings were reduced to one of the most robust plants per pot. Pot placement in the growth chamber was randomized. Soil humidity was controlled, and water content was maintained during the experiment at approximately 60% of water-holding capacity. The pots were variably rotated once per week. The plants were harvested 8 weeks after sowing.

2.3 Crop Performance

Before harvest, the efficiency of photosystem II (PSII) on lettuce plants was measured. The quantum yield of the PSII (QY-max) was determined (at light intensity 2400 mmol·m-2·s-1) by the fluorometer PAR-FluorPen FP 110-LM/S (Photon Systems Instruments, Drásov, Czech Republic), and the software FluorPen 1.1 was used for the analysis of the measured data. The determination of the normalized difference vegetation index (NDVI) was carried out too with PlantPen NDVI 310 (Photon System Instruments, Drásov, Czech Republic). The spectral reflectance of chlorophyll pigments, expressed as NDVI, is a measure of chlorophyll content (Garty et al. 2001) and its integrity (Castro and Sanchez-Azofeifa 2008) and correlates with the photosynthetic rate (Garty et al. 2001).

The lettuce shoots were cut at ground level, and the roots were gently cleaned of soil and washed with water. Fresh aboveground (AGB) and root biomass were estimated gravimetrically by weighing on the analytical scales. The lettuce shoots and roots were dried at 60 °C to a constant weight, and dry aboveground and root biomass were estimated gravimetrically by weighing on the analytical scales.

2.4 Soil Analyses for Physicochemical and Microbiological Attributes

A mixed soil sample was taken from each pot after harvesting the lettuce. Soil samples were homogenized by sieving through a sieve with a mesh size of 2 mm. Air-dried samples were analyzed for pH (ISO_10390, 2005) and electric conductivity (EC) (Hardie and Doyle 2012). Freeze-dried samples (− 50 °C) were used for the analyses of enzymatic activities: β-glucosidase (GLU), phosphatase (PHOS), urease (URE), arylsulphatase (ARS), and N-acetyl-β-D-glucosaminidase (NAG) were measured spectrophotometrically according to ISO_20130 2018. Nitrophenyl derivates of natural substrates were used for the measurement of GLU, PHOS, ARS, and NAG (at emission wavelength of 405 nm), and urea was a substate for URE (measured at wavelength of 650 nm); the values were expressed in μmol $NH_3 \cdot g^{-1} \cdot h^{-1}$ (urease) and in μmol (p-nitrophenol) $PNP \cdot g^{-1} \cdot h^{-1}$. The samples stored at 4 °C were used for the determination of dehydrogenase activity (DHA) using the standard method based on triphenyltetrazolium chloride (TTC values were expressed as μg $TPF \cdot g^{-1} \cdot h^{-1}$) (Małachowska-Jutsz and Matyja 2019), and for the determination of soil basal respiration (BR) and substrate-induced respirations (IR)—D-glucose (Glc-IR), L-alanine (Ala-IR), and L-arginine (Arg-IR) (Campbell et al. 2003) using the MicroResp® device (The James Hutton Institute, Scotland) and a colorimetric indication of CO_2 emission.

2.5 Statistical Analyses

The obtained data were statistically analyzed using the one-way analysis of variance (ANOVA) to evaluate the effects of the applied amendments. Treatment means were compared using the principal component analysis (PCA) and Tukey's HSD post hoc test (at a significance level of $p=0.05$). All data processing and statistical analyses were performed using the freely available software R, version 3.6.1. (R_Core_Team 2020). Pearson's correlation analysis was performed to measure the linear dependence between soil properties. Pearson's correlation coefficient was interpreted as follows: $0.0<r<0.3$ (negligible correlation), $0.3<r<0.5$ (low correlation), $0.5<r<0.7$ (moderate correlation), $0.7<r<0.9$ (high correlation), and $0.9<r<1.0$ (very high correlation) (Hinkle et al. 2003).

3 Results

3.1 Soil Chemical Properties

The application of wastewater sludge biochar (WWS) and food waste biochar (FW) with and without mixed zeolite (Z) and sawdust (SD) significantly affected soil pH as compared to control (Fig. 1a). All the amendments considerably reduced soil pH. Specifically, the highest significantly decreased soil pH was observed under FW + SD + Z and FW + SD as compared to control and other treatments (Fig. 1a). The same treatments on the other hand significantly enhanced the soil electrical conductivity (EC) as compared to control (Fig. 1b). Interestingly, the effect of other treatments remained statistically non-significant compared to the control (Fig. 1b).

3.2 Soil Extracellular Enzyme Activities

Remarkable variations were observed for soil enzyme activities under applied amendments (Fig. 2a–f). The application of FW + SD + Z resulted in significantly the highest dehydrogenase activity (DHA) as compared to the control and other amendments (Fig. 2a), which (all except WWS + SD) were significantly increased compared to the control as well. Similarly, the application of FW + SD + Z significantly enhanced β-glucosidase (GLU) and phosphatase (PHOS) activities as compared to the control and other amendments (Fig. 2b, c). The effect of other amendments in these cases (GLU and PHOS) remained statistically non-significant as compared to the control (Fig. 2b, c). Conversely, the nitrogen mineralizing enzymes, viz., urease (URE) and N-acetyl-β-D-glucosaminidase (NAG), were slightly increased under WWS + SD + Z, however, remained statistically non-significant relative to the control (Fig. 2d, e), while other treatments insignificantly reduced the activity of these enzymes as compared to the control (Fig. 2d, e). URE was markedly decreased in the AW biochar-treated soil; NAG and arylsulphatase (ARS) had the lowest values in the FW + SD variant. There was no clear effect of applied amendments observed for other treatments on ARS activity (Fig. 2f).

3.3 Soil Basal and Substrate-Induced Respiration

The application of WWS and FW with and without Z and SD considerably affected basal as well as substrate-induced respirations (SIR). FW + SD significantly enhanced the soil basal respiration (BR) as compared to the control, followed by AW and FW + SD + Z (Fig. 3a). Conversely, substrate-induced respirations were highest under the sole

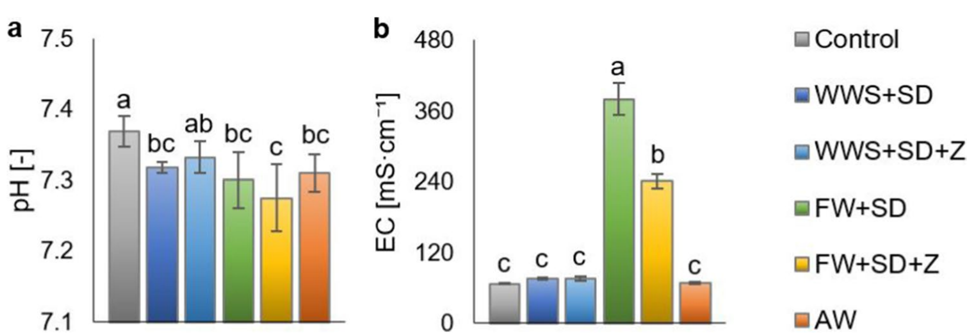

Fig. 1 The comparative responses of applied amendments on **a** soil pH and **b** soil electrical conductivity (EC). WWS + SD, wastewater sludge + sawdust biochar; WWS + SD + Z, wastewater sludge + sawdust + zeolite biochar; FW + SD, food waste biochar + sawdust biochar; FW + SD + Z, food waste + sawdust + zeolite biochar; AW, agricultural waste biochar. Different lowercase letters indicate statistically significant differences at the statistical significance level $p\leq0.05$. $n=3$, average values ± standard error of mean (error bars)

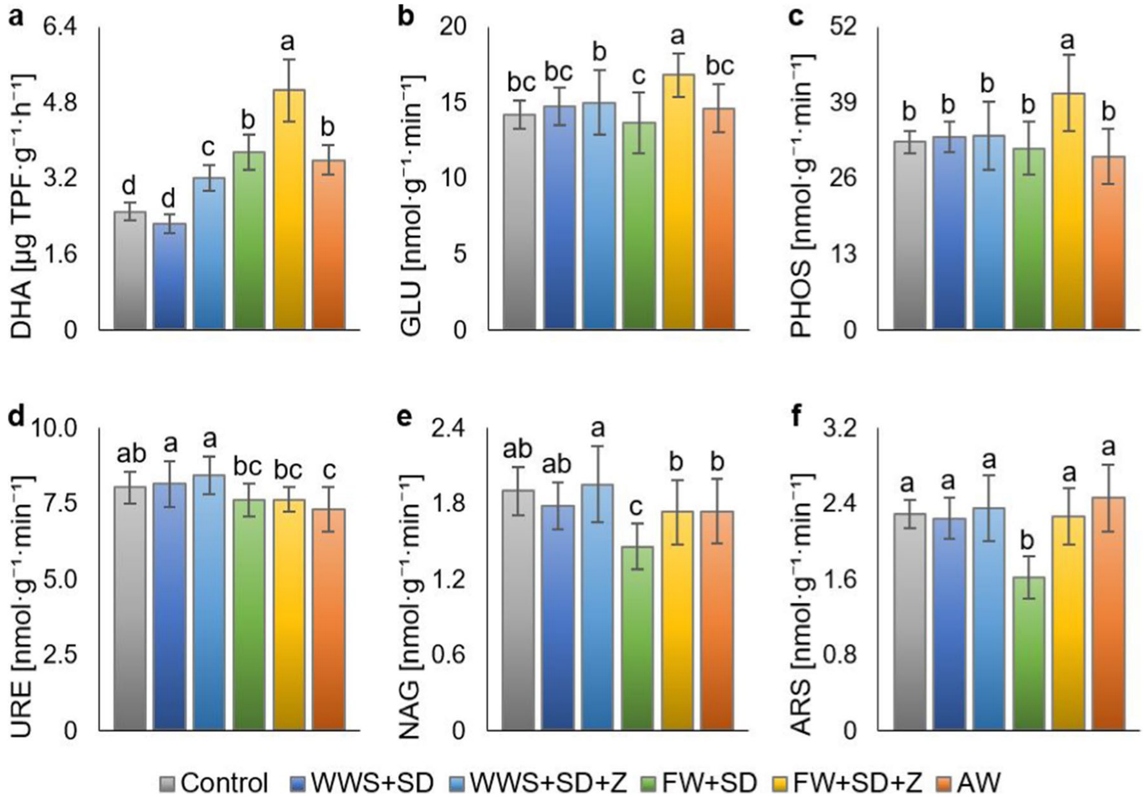

Fig. 2 The comparative responses of applied amendments on **a** dehydrogenase activity, **b** β-glucosidase activity, **c** phosphatase activity, **d** urease activity, **e** N-acetyl-β-D-glucosaminidase activity, and **f** arylsulphatase activity. WWS + SD, wastewater sludge + sawdust biochar; WWS + SD + Z, wastewater sludge + sawdust + zeolite biochar; FW + SD, food waste biochar + sawdust biochar; FW + SD + Z, food waste + sawdust + zeolite biochar; AW, agricultural waste biochar. Different lowercase letters indicate statistically significant differences at the statistical significance level $p \leq 0.05$. $n = 3$, average values ± standard error of mean (error bars)

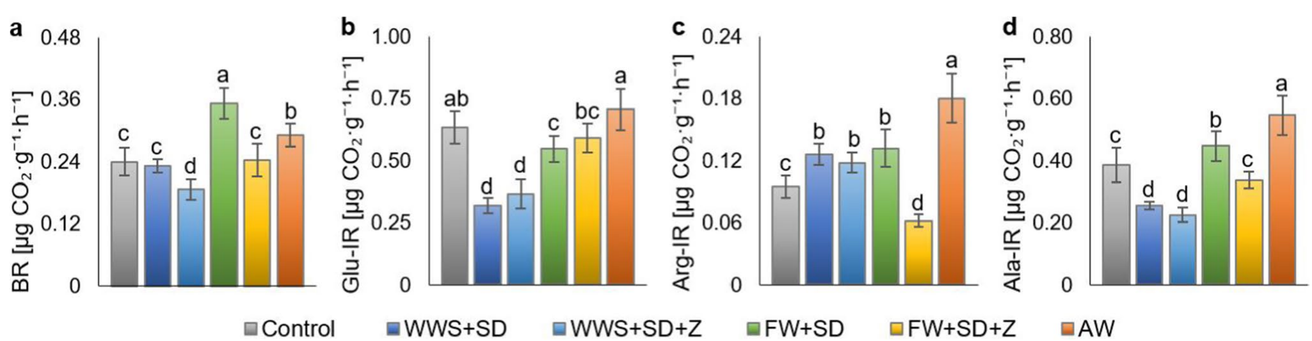

Fig. 3 The comparative responses of applied amendments on **a** basal respiration, **b** D-glucose induced respiration, **c** L-arginine induced respiration, and **d** L-alanin-induced respiration. WWS + SD, wastewater sludge + sawdust biochar; WWS + SD + Z, wastewater sludge + sawdust + zeolite biochar; FW + SD, food waste biochar + sawdust biochar; FW + SD + Z, food waste + sawdust + zeolite biochar; AW, agricultural waste biochar. Different lowercase letters indicate statistically significant differences at the statistical significance level $p \leq 0.05$. $n = 3$, average values ± standard error of mean (error bars)

application of AW as compared to other amendments and control (Fig. 3b–d). Glucose-induced respiration (Glu-IR) was significantly highest under AW and the lowest under WWS + SD as compared to the control (Fig. 3a). In the case of arginine-induced respiration (Arg-IR), all amendments except FW + SD + Z resulted in significantly higher respiration values as compared to the control (Fig. 3c), while alanin-induced respiration (Ala-IR) was the significantly highest in AW, followed by FW + SD, whereas WWS + SD and WWS + SD + Z variants exerted decreased Ala-IR (Fig. 3d).

3.4 Plant Growth and Photosynthetic Parameters

The application of biochars considerably affected plant growth and photosynthetic parameters (Figs. 4 and 5). The plant's aboveground fresh and dry biomass (AGB-fresh and AGB-dry) were significantly highest in WWS + SD + Z followed by WWS + SD as compared to the control (Fig. 4a, b); the same treatments also enhanced the root fresh weight (Root-fresh) (Fig. 4c). However, root dry weight was highest in AW (Fig. 4d). Regarding plant photosynthetic attributes, only slight changes were observed for QY-max and NDVI under the applied amendments as compared to the control (Fig. 5a, b). Specifically, QY-max was significantly higher under WWS + SD + Z and FW + SD (Fig. 5a). NDVI on the other hand showed higher values under WWS + SD, WWS + SD + Z, FW + SD, and WWS + SD + Z as compared to the control (Fig. 5b).

3.5 Pearson's Correlation and Principal Component and Analyses

Significant positive and negative correlations among soil and plant attributes were observed with Pearson's correlation analyses (Fig. 6). The extracted principal components (PC1 and PC2) by PCA on the other hand showed (82.7%) variability in the data set. PC1 contributed 46.7%, while PC2 contributed 27.7% of the total variations in observed parameters. The applied amendments were successfully distributed in 2 components of PCA (Fig. 7). This clearly indicated the differential roles of applied WWS, WWS + Z, FW, and FW + Z on observed soil and plant attributes. The most displaced parameters were soil pH, EC, DHA, BR, AGB-dry, and Arg-IR, suggesting them as the most robust parameters under applied amendments.

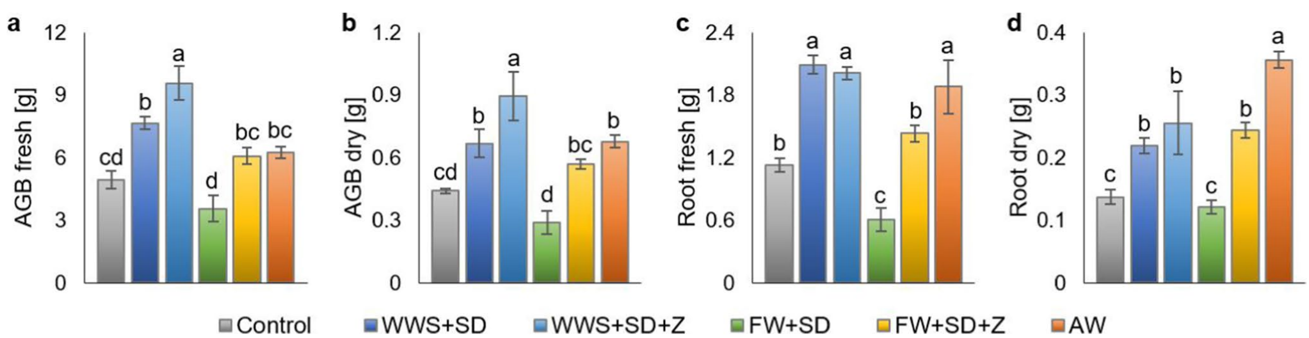

Fig. 4 The comparative responses of applied amendments on **a** aboveground fresh biomass, **b** aboveground dry biomass, **c** root fresh biomass, and **d** root dry biomass. WWS + SD, wastewater sludge + sawdust biochar; WWS + SD + Z, wastewater sludge + sawdust + zeolite biochar; FW + SD, food waste biochar + sawdust biochar; FW + SD + Z, food waste + sawdust + zeolite biochar; AW, agricultural waste biochar. Different lowercase letters indicate statistically significant differences at the statistical significance level $p \leq 0.05$. $n = 3$, average values ± standard error of mean (error bars)

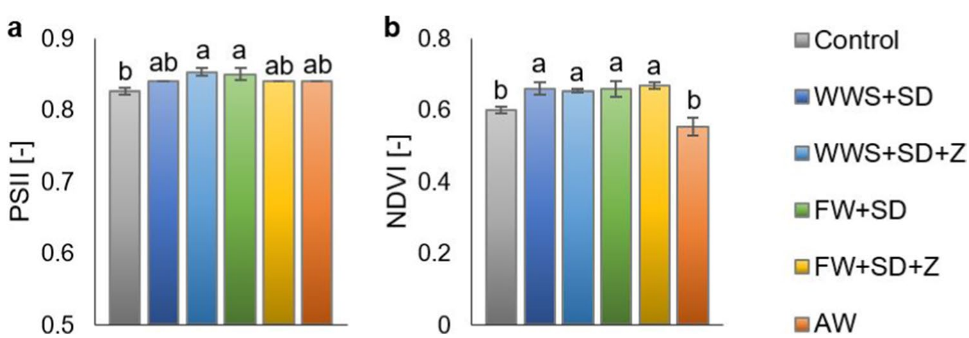

Fig. 5 The comparative responses of applied amendments on **a** quantum yield of photosystem II and **b** normalized difference vegetation index. WWS + SD, wastewater sludge + sawdust biochar; WWS + SD + Z, wastewater sludge + sawdust + zeolite biochar; FW + SD, food waste biochar + sawdust biochar; FW + SD + Z, food waste + sawdust + zeolite biochar; AW, agricultural waste biochar. Different lowercase letters indicate statistically significant differences at the statistical significance level $p \leq 0.05$. $n = 3$, average values ± standard error of mean (error bars)

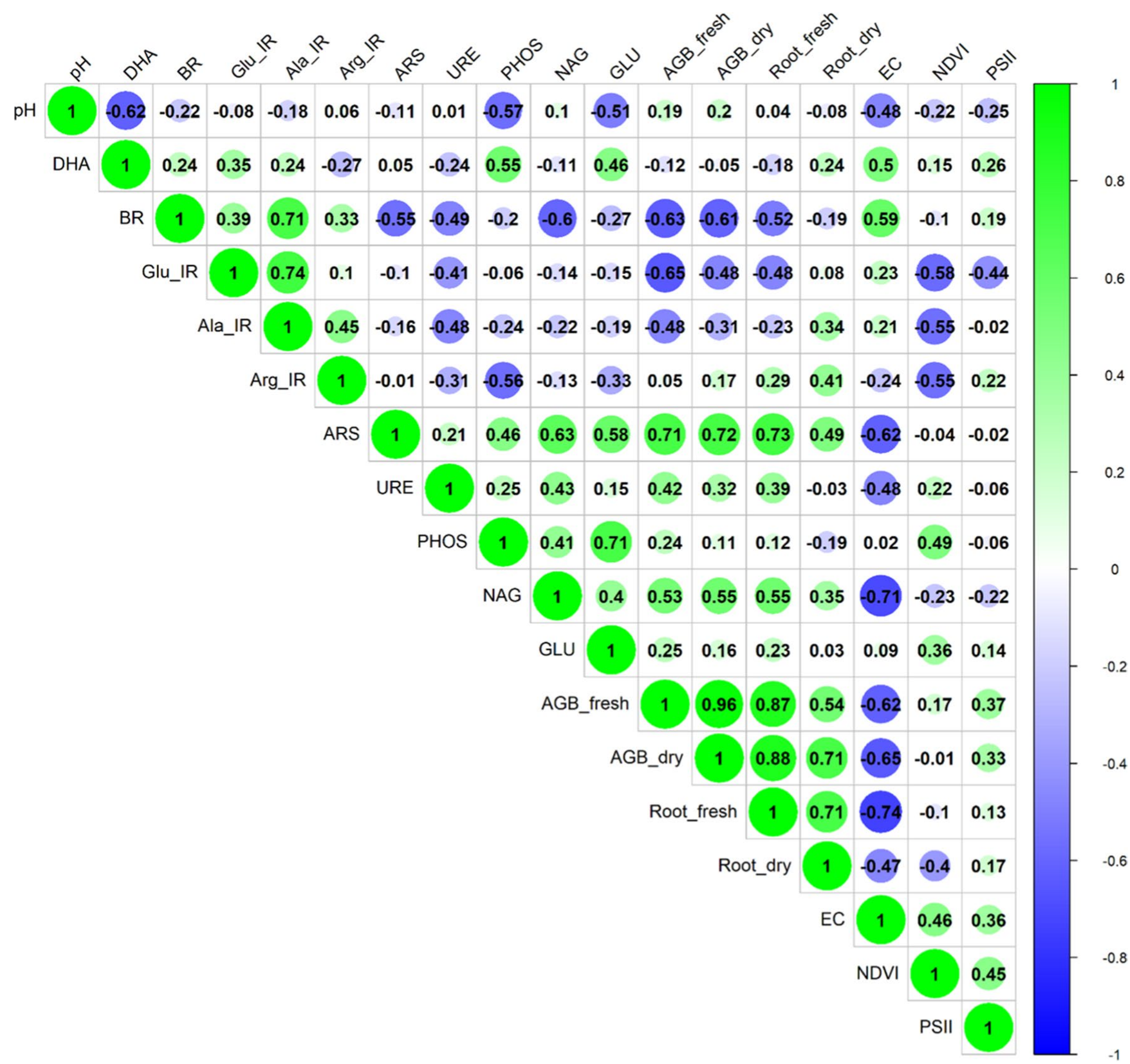

Fig. 6 The Pearson correlation matrix of observed parameters. Abbreviations are as follows: pH, soil reaction ($CaCl_2$); DHA, dehydrogenase activity; BR, basal respiration; Glu-IR, D-glucose-induced respiration; Ala-IR, L-alanin-induced respiration; Arg-IR, L-arginine-induced respiration; ARS, arylsulphatase; URE, urease activity; PHOS, phosphatase activity; NAG, N-acetyl-β-D-glucosaminidase; GLU, β-glucosidase activity; AGB_fresh, aboveground fresh biomass; AGB_dry, aboveground dry biomass; Root_fresh, root fresh biomass; Root_dry, root dry biomass; EC, electric conductivity; NDVI, normalized vegetation index; PSII, QY-max quantum yield of photosystem II. The correlation coefficients were determined at the statistical significance level $p \leq 0.05$

4 Discussion

The rapid increases in industrialization and overuse of chemical fertilizers have resulted in soil quality deterioration. Soil physicochemical properties are considered major factors influencing soil fertility and quality (Ding et al. 2016). In the present study, we evaluated the soil quality improvement through the application of different feedstock biochars, the novelty of which lies in the modification of pyrolysis conditions by adding zeolite and sawdust in varying concentrations (Ding and Jiang 2013; Lonova et al. 2022; Wang et al. 2022). This modification technique has been still weakly explored in previous research and offers several unique mechanisms for improving soil and plant attributes. Zeolite, known for its ion exchange properties, can effectively retain and slowly release essential plant nutrients; this feature was already revealed (Lonova et al. 2022), verified, and more broadly evaluated in this study. It was found that the mechanism of a zeolite-derived slowdown in the release of nutrients differed from traditional biochar amendments and expanded the potential of biochar as a soil fertility enhancer. Sawdust, being rich in organic matter, acts as a nutrient source for soil microorganisms. As it decomposes, it releases more nutrients such as nitrogen, phosphorus, and carbon in comparison to the biochar obtained from solely waste water sludge feedstock of pyrolysis (Nuagah et al. 2020; Lonova

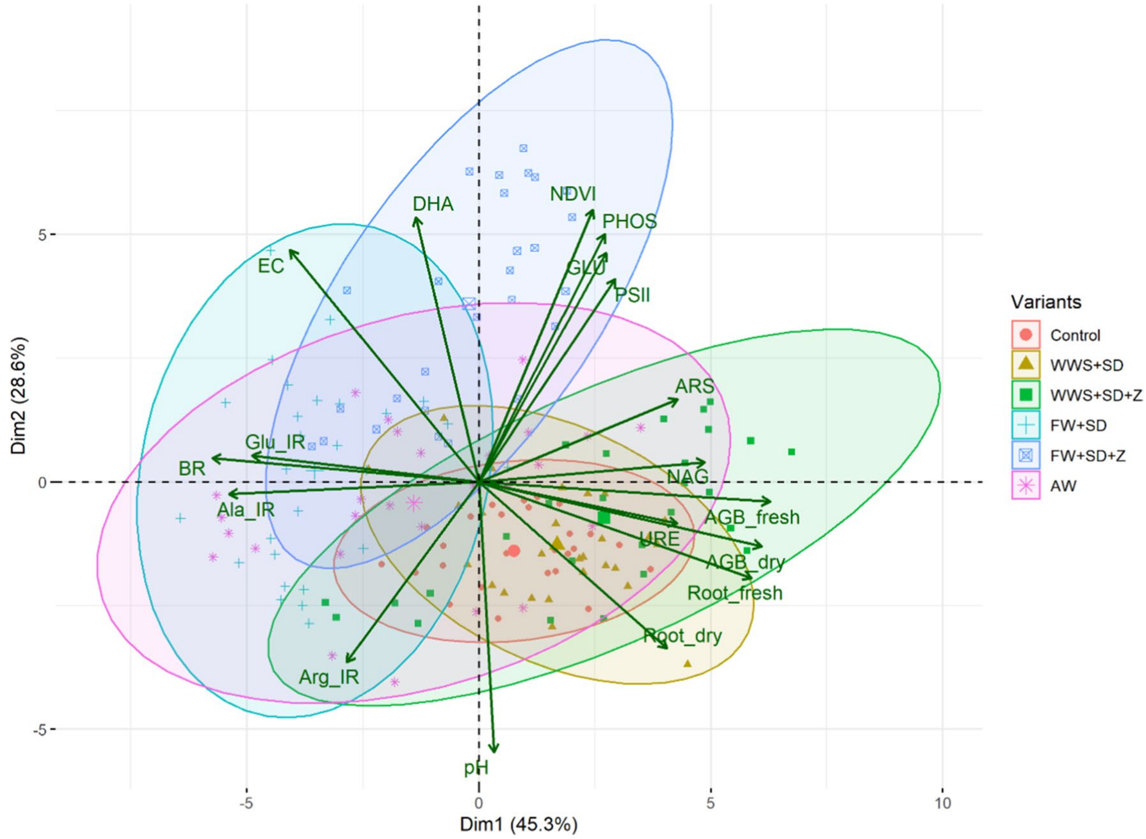

Fig. 7 The principal component analysis of observed soil and plant parameters. WWS + SD, wastewater sludge + sawdust biochar; WWS + SD + Z, wastewater sludge + sawdust + zeolite biochar; FW + SD, food waste biochar + sawdust biochar; FW + SD + Z, food waste + sawdust + zeolite biochar; AW, agricultural waste biochar. Abbreviations are as follows: pH, soil reaction ($CaCl_2$); DHA, dehydrogenase activity; BR, basal respiration; Glu-IR, D-glucose-induced respiration; Ala-IR, L-alanin-induced respiration; Arg-IR, L-arginine-induced respiration; ARS, arylsulphatase; URE, urease activity; PHOS, phosphatase activity; NAG, N-acetyl-β-D-glucosaminidase; GLU, β-glucosidase activity; AGB_fresh, aboveground fresh biomass; AGB_dry, aboveground dry biomass; Root_fresh, root fresh biomass; Root_dry, root dry biomass; EC, electric conductivity; NDVI, normalized vegetation index; PSII, QY-max quantum yield of photosystem II

et al. 2022), which supports microbial growth and activity and eventually contributes to enhanced soil health, nutrient cycling, and subsequent plant agronomic and physiological performance.

We specifically observed that the applied biochars differently impacted soil physicochemical properties in terms of EC and pH (Fig. 1a, b). Specifically, the application of all types of biochar greatly lowered the soil pH, whereby the highest decrease was found under the application of FW + SD + Z (Fig. 1a). These results are in accordance with Liu and Zhang (2012), who reported a reduction in soil pH after the application of biochar. This decrease in soil pH might be due to the production of acidic compounds produced due to the decomposition of organic matter which might have been promoted by biochar addition (Senesi and Plaza 2007; Dias et al. 2010). In addition, this might be due to the slow oxidation of biochar resulting in acidic functional groups which neutralize and ultimately lower the soil pH (Zavalloni et al. 2011; Liu and Zhang 2012). These results are further substantiated by the findings of Yin et al. (2017), who reported a decreased pH of soil after biochar addition.

Moreover, the applied FW + SD resulted in the highest EC, followed by FW + SD + Z (Fig. 1b). This might be due to the reason that biochar slowly releases nutrients into the soil, which increases the EC of the soil. This might also be due to the fact that biochar ash contains a reserve of nutrients, mostly cations, which after application to soil, are released into the soil solution and increase its EC (Yuan et al. 2015). In addition, the enhanced EC under biochar application might be the outcome of the retention of soil nutrients on the biochar surface which on the other hand might have improved nutrient solubility and availability that eventually resulted in a higher EC (Jaafar et al. 2015). Our results are in accordance with the previous works of Ali et al. (2020), who observed enhanced EC under the sole and combined application of different biochars and mineral fertilizers. In addition, a plethora of previous studies advocate the role of biochar in improving soil physicochemical properties (Singh et al. 2019; Mustafa, et al. 2022a). In another study, Zou et al. (2017) reported enhanced EC of soil due to the release of soluble compounds after the addition of red-mud-modified biochar in soil (Zou et al. 2017). However, it should be noted that the effect of applied biochar on soil physicochemical properties varies depending on soil types, rates of biochar addition, and biochar preparation methods. This further verified our hypothesis that the modification before pyrolysis has a strong influence on the resulting effects after biochar application on soil properties, which might be associated with the changes in chemical composition and properties resulting from modifications of feedstock before pyrolysis (Table 1). These relatively novel findings are innovative and, so far, scarcely reported (Nuagah et al. 2020; Lonova et al. 2022). Therefore, this study stressed that choosing an appropriate feedstock and its modification (mixing with sawdust and zeolite in this case) before pyrolysis can optimize biochar's ability to retain nutrients (Table 1) and improve soil properties (Fig. 1).

Soil microbes play a vital role in the regulation of many biogeochemical processes by secreting extracellular enzymes and catalyzing soil organic matter degradation through respiration (Sabale et al. 2015; Mustafa, et al. 2022a). Biochar has been acknowledged to promote microbial activity through the modification of soil properties. In fact, the addition of biochars is conductive to soil aggregation and soil structure improvement which ultimately improves the microenvironment for microbial activity (Tang et al. 2022). We found considerable variations in soil extracellular enzyme activities, namely, dehydrogenase, β-glucosidase, urease, phosphatase, arylsulphatase, and N-acetyl-β-D-glucosaminidase (Fig. 2a–f). The higher activity of DHA under applied FWB + SD + Z might be the outcome of enhanced labile forms of soil carbon, resulting in higher C mineralization potential as revealed by higher DHA activity in soil (Zhang and Sun 2014; Dubey et al. 2020). Moreover, the large differences observed in DHA activity under different biochars might be explained by the fact that a major part of the total carbon in applied FWB + SD + Z had been mineralized by microbes which resulted in higher DHA activity (Fig. 2a). This reflects a novel finding, which was previously revealed for wastewater sludge-based biochar (+ zeolite and sawdust) (Lonova et al. 2022). These differences were ascribed to the enhancement of soil organic matter degrading communities more in FWB + SD + Z as compared to other biochars, resulting in more C mineralization (DHA). These results agreed well with our previous study (Mustafa, et al. 2022b), reporting comparatively higher DHA under food waste biochar as compared to agricultural waste-derived biochars. Similarly, the same treatment enhanced β-glucosidase and phosphatase activities as compared to other treatments and controls (Fig. 2b, c). These results are in agreement with Irmak Yilmaz (2019), who reported a similar trend to the one observed in the present study for soil phosphatases and glucosidases. This higher activity could be related to the higher availability of nutrients (mainly C and P) for microbial use and the improvement of the microenvironment under applied biochars (Liang et al. 2014). Furthermore, we ascribed the changes in the activities of these enzymes, especially β-glucosidase (which degrades SOM) as the alteration of the decomposition rate regulated by substrate availability (Cárdenas-Aguiar et al. 2022). Moreover, the differences observed for β-glucosidase could be related to the variable input of fresh SOM resulting from the biochar additions. Urease and NAG activities are potential indicators of N mineralization in soil. Biochar addition has been reported to enhance their activity (Irmak Yilmaz 2019; Mustafa, et al. 2022c). We found almost similar activities of these enzymes in addition to arylsulphatases in under applied biochars as compared to the control (Fig. 2d–f). Such discrepancy could be explained by the variable N and S mineralizing activities of biochars potentially altering the microbial population under different biochar-amended soils and the chemical composition of applied feedstocks after modification with zeolite and sawdust (Table 1). These results are in accordance with Sun et al. (2014), who reported no change in ARS activity under the application of wood-derived biochar. Taken together, these findings suggested that the soil enzymes were most profound when biochars were mixed with sawdust and zeolite as compared to their single applications (Fig. 2), there are several mechanisms behind this such as (i) biochar owing to its high surface area can successfully adsorb enzymes and protect them from degradation and environmental fluctuation such as increased temperature and pH variations (Palansooriya et al. 2019), adding zeolite and sawdust can further enhance its adsorption capacity and render more protection to these enzymes (Mosa et al. 2020; Wang et al. 2021), (ii) zeolite owing to its porous structure can give additional protection and stabilize soil enzymes, while sawdust being rich in organic matter may create conducive microenvironment for soil enzyme activities (Yousefi et al. 2021; Lonova et al. 2022).

Biochar is a solid carbonaceous material and has been associated to influence microbial activities in terms of respiration. We found higher basal respiration (BR) as well as different substrate-induced respirations (SIR) under applied biochars (Fig. 3a–d). The enhanced respiration could be the outcome of increased microbial proliferation aided by the addition of organic matter under applied biochar (Haring et al. 2017). Moreover, the biochar addition might have provided a suitable microenvironment for an increased microbial population which ultimately improved microbial activity (Jin et al. 2008), as is evident from enhanced substrate-induced respirations in the present study as well

(Fig. 3b–d). The soil basal and substrate-induced respirations are considered effective indicators of microbial biomass and soil health. A number of previous studies describe the role of biochar in improving soil SIR (Gul et al. 2015; Karimi et al. 2019; Mustafa, et al. 2022c). In the present study, all SIR were higher under AW biochar as compared to others (Fig. 3b–d). This suggests the availability of easily mineralizable C was higher under AW soil as compared to others. Moreover, it could be related to enhanced biologically active compounds and a higher substrate for utilization (Herrmann et al. 2019).

Plant biomass accumulation and efficient photosynthesis are considered indicators of crop performance and contribute to overall crop productivity (Singh et al. 2020). Biochar obtained from various feedstocks has shown a tendency to improve crop agronomic as well as physiological performance (Lai et al. 2017; Iqbal et al. 2019; Ali et al. 2020; Singh et al. 2020). In the present study, the application of wastewater sewage sludge and agricultural waste-derived biochar together with zeolite and sawdust has shown the ability to improve crop growth (in terms of biomass accumulation) (Fig. 4). The high biomass production is directly related to higher nutrient uptake and their translocation to the plant tissues (Schmidt et al. 2014; Abideen et al. 2020). This was further supported by the positive correlation observed between nutrient mineralizing enzymes (GLU, PHOS, URE, etc.) and plant agronomic parameters (Figs. 6 and 7). Biochar has been recognized as a slow-release nutrient reserve (Ding et al. 2016). This is owing to the mechanisms by which biochar exchanges and retains ions on its surface and thus serves as a source of plant nutrients (Chan et al. 2007; Zheng et al. 2013). Similar positive effects of biochar have been reported in previous works (Dong et al. 2014; Lai et al. 2017; Mustafa, et al. 2022b, 2022c). Moreover, the improved photosynthetic activity under applied WWS + SD + Z (Fig. 5) might be the other reason for the enhanced agronomic performance of the crop. Taken together, this improvement in plant growth and physiological parameters of crops can be the outcome of directly enhanced plant nutrition and indirectly through the modification of soil physicochemical properties under biochar amendment (Li et al. 2020; Liu et al. 2022). For instance, adding zeolite and sawdust before pyrolysis can have a direct influence on improving crop performance through their mechanisms such as (i) increasing the efficiency of modified biochar to enhance nutrient availability which is related to higher ion exchange properties offered by zeolite and the decomposition of sawdust (Yousefi et al. 2013; Pant et al. 2020) and (ii) enhanced water-holding capacity offered by modified biochar and the porous structure of zeolite which enhances soil moisture and ultimately results in better crop growth and photosynthetic performance, as is observed in the present study (Fig. 5).

Moreover, the slight differences observed for different biochars in their effects on plant growth and physiology might be related to the differences in the composition of these biochars (Table 1) and further supported by our previous study (Mustafa, et al. 2022b).

5 Conclusion

This study comprehensively evaluated the differences in the efficacy of food, sewage sludge, and agricultural waste-derived biochars on soil quality and crop performance indicators. The activity of soil enzymes exhibited variable responses to distinct biochars, with carbon and phosphorus acquiring enzymes dehydrogenases, glucosidases, and phosphatases being highest in the soil amended with biochar obtained from combined food waste, sawdust, and zeolite, suggesting higher protection and stabilization of soil enzymes under this amendment. Furthermore, the application of biochar produced from food waste plus sole sawdust significantly enhanced soil basal respiration, while agricultural waste biochar was most effective in enhancing all substrate-induced respirations. This indicated varying substrate utilization by soil microbes influenced by the type of modified biochar. The combined wastewater sewage sludge biochar, sawdust, and zeolite were more effective in improving plant growth and physiological parameters, suggesting their role as sustainable soil amendments. In conclusion, these findings highlight the potential of biochar to enhance soil quality and crop performance, with the specific effects being influenced by the type of biochar used and its modification with zeolite and sawdust before pyrolysis. These results contribute to our understanding of biochar applications in agriculture and soil management, emphasizing the importance of considering feedstock selection and modification techniques to optimize the desired outcomes.

Author Contribution AM and MB conceptualized the research and prepared the first draft of managed resources. TH, JI, TB, and OM collected and analyzed the data. AK, JK, MH, and JH reviewed and edited the manuscript. All authors have read and agreed to the submission.

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Data Availability The data for this manuscript can be made available from corresponding author on a reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Abiad MG, Meho LI (2018) Food loss and food waste research in the Arab world: a systematic review. Food Secur 10:311–322. https://doi.org/10.1007/s12571-018-0782-7

Abideen Z, Koyro H-W, Huchzermeyer B, Gul B, Khan MA (2020) Impact of a biochar or a biochar-compost mixture on water relation, nutrient uptake and photosynthesis of Phragmites karka. Pedosphere 30:466–477. https://doi.org/10.1016/s1002-0160(17)60362-x

Ahmad R, Gao J, Gao Z, Khan A, Ali I, Fahad S (2022) Influence of biochar on soil nutrients and associated rhizobacterial communities of mountainous apple trees in Northern Loess Plateau China. Microorganisms 10:16. https://doi.org/10.3390/microorganisms10102078

Ali I, He L, Ullah S, Quan Z, Wei S, Iqbal A, Munsif F, Shah T, Xuan Y, Luo Y, Tianyuan L, Ligeng J (2020) Biochar addition coupled with nitrogen fertilization impacts on soil quality, crop productivity, and nitrogen uptake under double-cropping system. Food and Energy Sec. 9. https://doi.org/10.1002/fes3.208

Campbell CD, Chapman SJ, Cameron CM, Davidson MS, Potts JM (2003) A rapid microtiter plate method to measure carbon dioxide evolved from carbon substrate amendments so as to determine the physiological profiles of soil microbial communities by using whole soil. Appl Environ Microbiol 69:3593–3599. https://doi.org/10.1128/AEM.69.6.3593-3599.2003

Cárdenas-Aguiar E, Méndez A, Paz-Ferreiro J, Gascó G (2022) The effects of rabbit manure-derived biochar on soil health and quality attributes of two mine tailings. Sustainability 14:1866. https://doi.org/10.3390/su14031866

Castro KL, Sanchez-Azofeifa GA (2008) Changes in spectral properties, chlorophyll content and internal mesophyll structure of senescing Populus balsamifera and Populus tremuloides leaves. Sensors 8:51–69. https://doi.org/10.3390/s8010051

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. https://doi.org/10.1071/sr07109

Dias BO, Silva CA, Higashikawa FS, Roig A, Sanchez-Monedero MA (2010) Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. Bioresour Technol 101:1239–1246. https://doi.org/10.1016/j.biortech.2009.09.024

Ding Y, Liu Y, Liu S, Li Z, Tan X, Huang X, Zeng G, Zhou L, Zheng B (2016) Biochar to improve soil fertility. A review. Agron Sustain Dev 36. https://doi.org/10.1007/s13593-016-0372-z

Ding HS, Jiang H (2013) Self-heating co-pyrolysis of excessive activated sludge with waste biomass: energy balance and sludge reduction. Bioresour Technol 133:16–22. https://doi.org/10.1016/j.biortech.2013.01.090

Dong D, Feng Q, McGrouther K, Yang M, Wang H, Wu W (2014) Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field. J Soils Sediments 15:153–162. https://doi.org/10.1007/s11368-014-0984-3

Dubey RK, Dubey PK, Chaurasia R, Singh HB, Abhilash PC (2020) Sustainable agronomic practices for enhancing the soil quality and yield of Cicer arietinum L. under diverse agroecosystems. J Environ Manage 262:110284. https://doi.org/10.1016/j.jenvman.2020.110284

Eduah JO, Nartey EK, Abekoe MK, Breuning-Madsen H, Andersen MN (2019) Phosphorus retention and availability in three contrasting soils amended with rice husk and corn cob biochar at varying pyrolysis temperatures. Geoderma 341:10–17. https://doi.org/10.1016/j.geoderma.2019.01.016

El-Naggar A, Lee SS, Awad YM, Yang X, Ryu C, Rizwan M, Rinklebe J, Tsang DCW, Ok YS (2018) Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. Geoderma 332:100–108. https://doi.org/10.1016/j.geoderma.2018.06.017

Garty J, Tamir O, Hassid I, Eshel A, Cohen Y, Karnieli A, Orlovsky L (2001) Photosynthesis, chlorophyll integrity, and spectral reflectance in lichens exposed to air pollution. J Environ Qual 30:884–893. https://doi.org/10.2134/jeq2001.303884x

Gul S, Whalen JK, Thomas BW, Sachdeva V, Deng H (2015) Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agric Ecosyst Environ 206:46–59. https://doi.org/10.1016/j.agee.2015.03.015

Hardie M, Doyle R (2012) Measuring soil salinity. Methods Mol Biol 913:415–425

Haring V, Manka'abusi D, Akoto-Danso EK, Werner S, Atiah K, Steiner C, Lompo DJP, Adiku S, Buerkert A, Marschner B (2017) Effects of biochar, waste water irrigation and fertilization on soil properties in West African urban agriculture. Sci Rep 7:10738. https://doi.org/10.1038/s41598-017-10718-y

He M, Xiong X, Wang L, Hou D, Bolan NS, Ok YS, Rinklebe J, Tsang DCW (2021) A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils. J Hazard Mater 414:125378. https://doi.org/10.1016/j.jhazmat.2021.125378

Herrmann L, Lesueur D, Robin A, Robain H, Wiriyakitnateekul W, Brau L (2019) Impact of biochar application dose on soil microbial communities associated with rubber trees in North East Thailand. Sci Total Environ 689:970–979. https://doi.org/10.1016/j.scitotenv.2019.06.441

Hinkle DE, Wiersma W, Jurs SG (2003) Applied statistics for the behavioral sciences, 5th edn. Houghton Mifflin, Boston, Mass

Holatko J, Bielska L, Hammerschmiedt T, Kucerik J, Mustafa A, Radziemska M, Kintl A, Baltazar T, Latal O, Brtnicky M (2022) Cattle manure fermented with biochar and humic substances improve the crop biomass, microbiological properties and nutrient status of soil. Agronomy 12:368. https://doi.org/10.3390/agronomy12020368

Huang H-J, Yang T, Lai F-Y, Wu G-Q (2017) Co-pyrolysis of sewage sludge and sawdust/rice straw for the production of biochar. J Anal Appl Pyrolysis 125:61–68. https://doi.org/10.1016/j.jaap.2017.04.018

IBI (2015) Standardized product definition and product testing guidelines for biochar that is used in soil. international biochar initiative. http://www.biochar-international.org/characterizationstandard

Iqbal A, He L, Khan A, Wei S, Akhtar K, Ali I, Ullah S, Munsif F, Zhao Q, Jiang L (2019) Organic manure coupled with inorganic fertilizer: an approach for the sustainable production of rice by improving soil properties and nitrogen use efficiency. Agronomy 9:651. https://doi.org/10.3390/agronomy9100651

Irmak Yilmaz F (2019) Impact of biochar and animal manure on some biological and chemical properties of soil. Appl Ecol Environ Res. 17. https://doi.org/10.15666/aeer/1704_88658876

ISO_10390 (2005) Soil quality - determination of pH. International Organization for Standardization, Geneva, Switzerland

Jaafar NM, Clode PL, Abbott LK (2015) Soil microbial responses to biochars varying in particle size, surface and pore properties. Pedosphere 25:770–780. https://doi.org/10.1016/s1002-0160(15)30058-8

Jin H, Lehmann J, Thies JE (2008) September. Soil microbial community response to amending maize soils with maize stover charcoal. In: Proceedings of the 2008 conference of international biochar initiative. United States Department of Agriculture, Newcastle, UK, pp 8–10

Karimi A, Moezzi A, Chorom M, Enayatizamir N (2019) Application of biochar changed the status of nutrients and biological activity in a calcareous soil. J Soil Sci Plant Nutr 20:450–459. https://doi.org/10.1007/s42729-019-00129-5

Khan N, Chowdhary P, Gnansounou E, Chaturvedi P (2021) Biochar and environmental sustainability: emerging trends and techno-economic perspectives. Bioresour Technol 332:125102. https://doi.org/10.1016/j.biortech.2021.125102

Kumar A, Singh E, Singh L, Kumar S, Kumar R (2021) Carbon material as a sustainable alternative towards boosting properties of urban soil and foster plant growth. Sci Total Environ 751:141659. https://doi.org/10.1016/j.scitotenv.2020.141659

Lai L, Ismail MR, Muharam FM, Yusof MM, Ismail R, Jaafar NM (2017) Effects of rice straw biochar and nitrogen fertilizer on rice growth and yield. Asian J Crop Sci 9:159–166. https://doi.org/10.3923/ajcs.2017.159.166

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota – a review. Soil Biol Biochem 43:1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Li X, Shao X, Ding F, Yuan Y, Li R, Yang X, Gao C, Miao Q (2020) Effects of effective microorganisms biochar-based fertilizer on photosynthetic characteristics and chlorophyll content of flue-cured tobacco under water-saving irrigation strategies. Chil J Agric Res 80:422–432. https://doi.org/10.4067/s0718-58392020000300422

Liang C, Zhu X, Fu S, Méndez A, Gascó G, Paz-Ferreiro J (2014) Biochar alters the resistance and resilience to drought in a tropical soil. Environ Res Lett 9:064013. https://doi.org/10.1088/1748-9326/9/6/064013

Liu XH, Zhang XC (2012) Effect of biochar on pH of alkaline soils in the Loess Plateau: results from incubation experiments. Int J Agric Biol 14:745–750

Liu M, Linna C, Ma S, Ma Q, Guo J, Wang F, Wang L (2022) Effects of biochar with inorganic and organic fertilizers on agronomic traits and nutrient absorption of soybean and fertility and microbes in purple soil. Front Plant Sci 13:871021. https://doi.org/10.3389/fpls.2022.871021

Lonova K, Holatko J, Hammerschmiedt T, Mravcova L, Kucerik J, Mustafa A, Kintl A, Naveed M, Racek J, Grulichova M, Miklasova M, Brtnicky M (2022) Microwave pyrolyzed sewage sludge: influence on soil microbiology, nutrient status, and plant biomass. Chem Biol Technol Agric 9:92. https://doi.org/10.1186/s40538-022-00354-8

Majumder S, Neogi S, Dutta T, Powel MA, Banik P (2019) The impact of biochar on soil carbon sequestration: meta-analytical approach to evaluating environmental and economic advantages. J Environ Manage 250:109466. https://doi.org/10.1016/j.jenvman.2019.109466

Małachowska-Jutsz A, Matyja K (2019) Discussion on methods of soil dehydrogenase determination. Int J Environ Sci Technol 16:7777–7790. https://doi.org/10.1007/s13762-019-02375-7

Mohan D, Sarswat A, Ok YS, Pittman CU Jr (2014) Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. Bioresour Technol 160:191–202. https://doi.org/10.1016/j.biortech.2014.01.120

Mosa A, El-Ghamry A, Tolba M (2020) Biochar-supported natural zeolite composite for recovery and reuse of aqueous phosphate and humate: batch sorption–desorption and bioassay investigations. Environ Technol Innov 19:100807. https://doi.org/10.1016/j.eti.2020.100807

Mustafa A, Brtnicky M, Hammerschmiedt T, Kucerik J, Kintl A, Chorazy T, Naveed M, Skarpa P, Baltazar T, Malicek O, Holatko J (2022a) Food and agricultural wastes-derived biochars in combination with mineral fertilizer as sustainable soil amendments to enhance soil microbiological activity, nutrient cycling and crop production. Front Plant Sci 13:1028101. https://doi.org/10.3389/fpls.2022.1028101

Mustafa A, Holatko J, Hammerschmiedt T, Kucerik J, Skarpa P, Kintl A, Racek J, Baltazar T, Malicek O, Brtnicky M (2022b) Comparison of the responses of soil enzymes, microbial respiration and plant growth characteristics under the application of agricultural and food waste-derived biochars. Agronomy 12:2428. https://doi.org/10.3390/agronomy12102428

Mustafa A, Holatko J, Hammerschmiedt T, Kucerik J, Baltazar T, Kintl A, Malicek O, Havlicek Z, Brtnicky M (2022c) Unveiling the impacts of biochar, manure and their optimal combinations on microbiological soil health indicators and lettuce biomass. Agronomy 12:2307. https://doi.org/10.3390/agronomy12102307

Nan H, Mašek O, Yang F, Xu X, Qiu H, Cao X, Zhao L (2022) Minerals: a missing role for enhanced biochar carbon sequestration from the thermal conversion of biomass to the application in soil. Earth-Sci Rev 234:104215. https://doi.org/10.1016/j.earscirev.2022.104215

Naveed M, Tanvir B, Xiukang W, Brtnicky M, Ditta A, Kucerik J, Subhani Z, Nazir MZ, Radziemska M, Saeed Q, Mustafa A (2021) Co-composted biochar enhances growth, physiological, and phytostabilization efficiency of Brassica napus and reduces associated health risks under chromium stress. Front Plant Sci 12:775785. https://doi.org/10.3389/fpls.2021.775785

Nguyen DH, Scheer C, Rowlings DW, Grace PR (2015) Rice husk biochar and crop residue amendment in subtropical cropping soils: effect on biomass production, nitrogen use efficiency and greenhouse gas emissions. Biol Fertil Soils 52:261–270. https://doi.org/10.1007/s00374-015-1074-4

Nuagah MB, Boakye P, Oduro-Kwarteng S, Sokama-Neuyam YA (2020) Valorization of faecal and sewage sludge via pyrolysis for application as crop organic fertilizer. J Anal Appl Pyrolysis 151:9. https://doi.org/10.1016/j.jaap.2020.104903

Palansooriya KN, Wong JTF, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Bolan NS, Wang H, Ok YS (2019) Response of microbial communities to biochar-amended soils: a critical review. Biochar 1:3–22

Pant PK, Mishra A, Bhatt P (2020) Amelioration of soil: based on mineral (zeolite) source: a review. Trends Tech Sci Res. 4:555626. https://doi.org/10.19080/TTSR.2020.04.555626

R_Core_Team. (2020). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. PLoS One 8:e66428. https://doi.org/10.1371/journal.pone.0066428

Sabale RP, Shabeer TPA, Utture SC, Banerjee K, Oulkar DP, Adsule PG, Deshmukh MB (2015) Kresoxim methyl dissipation kinetics and its residue effect on soil extra-cellular and intra-cellular enzymatic activity in four different soils of India. J Environ Sci Health B 50:90–98. https://doi.org/10.1080/03601234.2015.975600

Schmidt H-P, Kammann C, Niggli C, Evangelou MWH, Mackie KA, Abiven S (2014) Biochar and biochar-compost as soil amendments to a vineyard soil: influences on plant growth, nutrient uptake, plant health and grape quality. Agric Ecosyst Environ 191:117–123. https://doi.org/10.1016/j.agee.2014.04.001

Senesi N, Plaza C (2007) Role of Humification Processes in recycling organic wastes of various nature and sources as soil amendments. CLEAN – Soil. Air, Water 35:26–41. https://doi.org/10.1002/clen.200600018

Shahbaz AK, Adnan Ramzani PM, Saeed R, Turan V, Iqbal M, Lewinska K, Abbas F, Saqib M, Tauqeer HM, Iqbal M, Fatima M, Rahman MU (2019) Effects of biochar and zeolite soil amendments with foliar proline spray on nickel immobilization, nutritional quality and nickel concentrations in wheat. Ecotoxicol Environ Saf 173:182–191. https://doi.org/10.1016/j.ecoenv.2019.02.025

Singh R, Singh P, Singh H, Raghubanshi AS (2019) Impact of sole and combined application of biochar, organic and chemical fertilizers on wheat crop yield and water productivity in a dry tropical agro-ecosystem. Biochar 1:229–235. https://doi.org/10.1007/s42773-019-00013-6

Singh R, Srivastava P, Bhadouria R, Yadav A, Singh H, Raghubanshi AS (2020) Combined application of biochar and farmyard manure reduces wheat crop eco-physiological performance in a tropical dryland agro-ecosystem. Energy Ecol 5:171–183. https://doi.org/10.1007/s40974-020-00159-1

Sun Y, Gao B, Yao Y, Fang J, Zhang M, Zhou Y, Chen H, Yang L (2014) Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. Chem Eng J 240:574–578. https://doi.org/10.1016/j.cej.2013.10.081

Tang H, Chen M, Wu P, Faheem M, Feng Q, Lee X, Wang S, Wang B (2022) Engineered biochar effects on soil physicochemical properties and biota communities: a critical review. Chemosphere 311:137025. https://doi.org/10.1016/j.chemosphere.2022.137025

Thomsen TP, Sarossy Z, Gobel B, Stoholm P, Ahrenfeldt J, Frandsen FJ, Henriksen UB (2017) Low temperature circulating fluidized bed gasification and co-gasification of municipal sewage sludge. Part 1: process performance and gas product characterization. Waste Manag 66:123–133. https://doi.org/10.1016/j.wasman.2017.04.028

Ullah S, Zhao Q, Wu K, Ali I, Liang H, Iqbal A, Wei S, Cheng F, Ahmad S, Jiang L, Gillani SW, Amanullah Anwar S, Khan Z (2021) Biochar application to rice with (15)N-labelled fertilizers, enhanced leaf nitrogen concentration and assimilation by improving morpho-physiological traits and soil quality. Saudi J Biol Sci 28:3399–3413. https://doi.org/10.1016/j.sjbs.2021.03.003

Wali F, Sardar S, Naveed M, Asif M, Nezhad MTK, Baig KS, Bashir M, Mustafa A (2022) Effect of consecutive application of phosphorus-enriched biochar with different levels of P on growth performance of maize for two successive growing seasons sustainability. Sustainability 14:1987. https://doi.org/10.3390/su14041987

Wang Y, Song X, Xu Z, Cao X, Song J, Huang W, Ge X, Wang H (2021) Adsorption of nitrate and ammonium from water simultaneously using composite adsorbents constructed with functionalized biochar and modified zeolite. Water Air Soil Pollut 232:198. https://doi.org/10.1007/s11270-021-05145-9

Wang MY, Zhao YZ, Wang XH (2022) Preparation and assessment of granular substrate from wastewater post-coagulation sludge towards maximum phosphate adsorption and erosion wear resistance. Resour Conserv Recycl 184:9. https://doi.org/10.1016/j.resconrec.2022.106429

Xia Y, Tang Y, Shih K, Li B (2020) Enhanced phosphorus availability and heavy metal removal by chlorination during sewage sludge pyrolysis. J Hazard Mater 382:121110. https://doi.org/10.1016/j.jhazmat.2019.121110

Yin D, Wang X, Peng B, Tan C, Ma LQ (2017) Effect of biochar and Fe-biochar on Cd and As mobility and transfer in soil-rice system. Chemosphere 186:928–937. https://doi.org/10.1016/j.chemosphere.2017.07.126

Yousefi J, Younesi H, Ghasempoury SM (2013) Co-composting of municipal solid waste with sawdust: improving compost quality. CLEAN – Soil. Air, Water 41:185–194. https://doi.org/10.1002/clen.201100315

Yousefi R, Amooei AA, Amel Sakhi M, Karimi A (2021) Experimental study on influence of using urease enzyme on stabilized sandy soil's engineering property by zeolite and sawdust. Int J Marit Technol 15:17–27

Yuan Y, Liu T, Fu P, Tang J, Zhou S (2015) Conversion of sewage sludge into high-performance bifunctional electrode materials for microbial energy harvesting. J Mater Chem 3:8475–8482. https://doi.org/10.1039/c5ta00458f

Zaidun SW, Jalloh MB, Awang A, Sam LM, Besar NA, Musta B, Ahmed OH, Omar L (2019) Biochar and clinoptilolite zeolite on selected chemical properties of soil cultivated with maize (Zea mays L). Eurasian J Soil Sci 8:1–10. https://doi.org/10.18393/ejss.468100

Zavalloni C, Alberti G, Biasiol S, Vedove GD, Fornasier F, Liu J, Peressotti A (2011) Microbial mineralization of biochar and wheat straw mixture in soil: a short-term study. Appl Soil Ecol 50:45–51. https://doi.org/10.1016/j.apsoil.2011.07.012

Zhang L, Sun X (2014) Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar. Bioresour Technol 171:274–284. https://doi.org/10.1016/j.biortech.2014.08.079

Zheng H, Wang Z, Deng X, Zhao J, Luo Y, Novak J, Herbert S, Xing B (2013) Characteristics and nutrient values of biochars produced from giant reed at different temperatures. Bioresour Technol 130:463–471. https://doi.org/10.1016/j.biortech.2012.12.044

Zou Q, An W, Wu C, Li W, Fu A, Xiao R, Chen H, Xue S (2017) Red mud-modified biochar reduces soil arsenic availability and changes bacterial composition. Environ Chem Lett 16:615–622. https://doi.org/10.1007/s10311-017-0688-1