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ORIGINAL PAPER

Effects of MicroChar on Phosphorus Availability and Pea Growth

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Abstract

This study examines the practical application of MicroChar to enhance phosphorus availability in nutrient-deficient soils. The char was enriched with organic nutrients and inoculated with a mixed microbial culture of bacteria and fungal spores. Combining incubation trials with two soils and pot experiments amending Regosol soil with 2% MicroChar, we examined impacts under optimal soil water and drought conditions, using pea (*Pisum sativum* L) as an indicator crop. While initially increasing soluble phosphorus concentrations in soil pore water, MicroChar application led to sustained enhancements in phosphorus availability throughout incubations and pot experiments, benefiting plant growth under optimal conditions. Under optimal water conditions, MicroChar also stimulated pea root, shoot, and pod growth, implying enhanced phosphorus nutrition. However, drought stress suppressed plant response regardless of phosphorus availability. Overall, MicroChar augmented plant-accessible phosphorus in phosphorus-deficient Regosol, bearing critical implications for sustainable phosphorus management in agriculture. Strategic MicroChar application shows potential to improve phosphorus efficiency. Further trials across diverse soils and climates would extend these findings.

Keywords Biochar · Nutrient increase · Phosphorus · Drought soil · Crop growth

Abbreviations

%	Percent
ANOVA	Analysis of variance
BET	Brunauer-Emmett-Teller
BHT	Butylated hydroxytoluene
B	Biochar
C	Carbon
C/N	Carbon to nitrogen ratio
C/ha	Carbon per hectare
CC	Non-amended soil
CEC	Cation exchange capacity
Ca	Calcium
Catot	Total calcium
Ctot	Total carbon
DG	Diglycerides
DS	Drought-stressed conditions
DW	Dry weight
EC	Electrical conductivity
FB	MicroChar
FB-S	MicroChar + Hoagland spiked
FM2%	Cambisol + 2% MicroChar
Fe	Iron
H	Hoagland solution
HPLC	High-performance liquid chromatography
HPLC-UV/VIS	High-performance liquid chromatography with ultraviolet-visible detection
HSD	Tukey's honestly significant difference
ICP-OES	Inductively coupled plasma optical emission spectrometry
ISO/TS	International Organization for Standardization/Technical Specification
K	Potassium
Ktot	Total potassium

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LOI	Loss on ignition
Mg	Magnesium
Mgtot	Total magnesium
Mn	Manganese
N	Nitrogen
NH4	Ammonium
NO3	Nitrate
NPK	Nitrogen, phosphorus, and potassium
Ntot	Total nitrogen
OM	Organic matter
Opt.	Optimal conditions
P	Phosphorus
PO4	Phosphate
Ptot	Total phosphorus
RDA	Redundancy analysis
RM2%	Regosol + 2% MicroChar
S	Sulfur
SB	Sum of bases
SO4	Sulfate
SOC	Soil organic carbon
SOM	Soil organic matter
SPSS	Statistical Package for the Social Sciences
Stot	Total sulfur
UV/VIS	Ultraviolet-visible spectroscopy
WHC	Water holding capacity
Zn	Zinc
$g.cm^{-3}$	Grams per cubic centimeter
$g.kg^{-1}$	Grams per kilogram
mL/day	Milliliters per day
mL/min	Milliliters per minute
mg/L	Milligrams per liter
mg/kg	Milligrams per kilogram
m^3m^{-3}	Cubic meter per cubic meter
pH	Potential of hydrogen
w/w	Weight/weight
$\mu S.cm^{-1}$	Microsiemens per centimeter

1 Introduction

Within the soil matrix, essential nutrients, including carbon, nitrogen, and phosphorus, are inherently present, representing crucial elements for the growth and development of plants. A thriving microbial population within healthy soil catalyses nutrient cycling, enriching the soil and ensuring its fertility. Soil health is intricately linked with the environment's overall health, making sustainable soil management imperative for ensuring the long-term vitality of the planet and its inhabitants. Unfortunately, soil is highly susceptible to degradation caused by many factors, including climate change, excessive use of chemical fertilizers, erosion, and suboptimal management practices (Lin et al. 2019). Europe has observed an increase in drought events in recent years, with substantial portions of Europe recently experiencing extreme temperature conditions (Toreti et al. 2022). Drought conditions can deteriorate soil hydraulic properties, leading to erosion and nutrient loss (Madadgar et al. 2017; Verheijen et al. 2010). To confront these challenges, it becomes imperative to curtail carbon loss from the soil and consider potential alternatives, such as using organic fertilizers, to replenish carbon compounds (Tramblay et al. 2020). Loss of carbon from the soil leads to a reduction in SOM, which leads to a decline in soil fertility. (Castellini et al. 2021; Page et al. 2020).

Nutrient deficiencies in soil, particularly those of nitrogen, phosphorus, and potassium (NPK), present widespread challenges within global agricultural systems, exerting detrimental effects on plant growth and crop yields. These three macronutrients are indispensable elements vital for the growth and development of plants, and their global reserves are constrained, potentially facing depletion within the coming decades should prevailing patterns persist (Walan et al. 2014). To address this concern, researchers are actively investigating recycling and reuse strategies for phosphorus and potassium, coupled with the adoption of innovative farming practices, to diminish reliance on the extraction of fresh reserves (Glaser and Lehr 2019).

Previous studies have shown that the effectiveness of biochar can vary significantly depending on the feedstock and pyrolysis conditions. This variability makes it difficult to draw general conclusions about the benefits of biochar and necessitates further research on specific biochar types. While some studies have examined the effects of biochar on soil properties, few have focused on nutrient availability, particularly phosphorus. This study addresses this gap by directly investigating the impact of MicroChar on phosphorus availability in two contrasting soils. Biochar, a stable carbonaceous material generated through pyrolysis, has demonstrated potential in enhancing various soil-related aspects, including water retention, nutrient release, crop productivity, soil stability, and microbial activity, as evidenced by certain studies (Kammann et al. 2011; Schmidt et al. 2021).

One noteworthy concern associated with commercial biochar pertains to its fine and dusty nature, which can pose challenges during application and may result in some loss during the process (Wang et al. 2016; Zhou et al. 2018). Conversely, MicroChar, derived from biowaste and pyrolyzed at temperatures ranging from 450 to 600 °C, possesses a mustard seed-like shape (Nguyen et al. 2017) and holds promise as a more practical option for field application. The impact of biochar on drought mitigation has not been studied sufficiently. This study addresses this knowledge

gap by investigating the effects of MicroChar under both optimal and drought conditions. MicroChar is an innovative biochar product engineered to enhance soil health and nutrient availability. Prior studies have not elucidated biochar amendments targeted for micronutrients like phosphorus. However, many farmers remain hesitant to adopt these amendments due to concerns about their financial viability (Maroušek et al. 2019). Nevertheless, uncertainties remain regarding its broader ecological impacts and effectiveness across diverse crop types, particularly nitrogen-fixing plants. *Pisum sativum* L., an example of a nitrogen-fixing crop (Akinnuoye-Adelabu et al. 2019), displays high sensitivity to drought and extreme light conditions, which can hinder root and biomass growth despite its adaptive mechanisms. Multivariate analytical techniques, including principal component analysis (PCA) and redundancy analysis (RDA) were used to analyze inter-relationships between soil chemical parameters and connections with plant growth responses.

This study investigates the effects of MicroChar, a novel biochar, on phosphorus availability, drought mitigation, and pea plant growth in two contrasting soils, selected to represent different textures and nutrient levels. We hypothesize that (i) MicroChar will increase plant-available phosphorus concentrations in the soil and (ii) improve plant growth parameters, such as shoot biomass, root length, and pod yield, under (iii) both optimal and drought conditions compared to conventional biochar and non-amended soil.

2 Materials and Methods

2.1 Soils and Additives

This study utilized two nutrient-deficient soil types to evaluate the efficacy of MicroChar. Additionally, a commercially available biochar was included for comparison.

2.1.1 Soil Collection and Preparation

Two soil types with low nutrients were used for this study. The first soil was sampled from an arable field in Zvěřínek (Czech Republic, CZE) (50.1532° N, 15.0057° E). The soil type was determined to be Regosol and is found in a historically drought-prone location. The second soil was sampled in a Forest area in Jevany (CZE) (49.9706° N, 14.8105° E). This soil was characterized as Cambisol. At each site, soil was collected from 0 to 35 cm depth, corresponding to the primary rooting zone of pea plants. The collected soil was stored air-dry at room temperature in a greenhouse before use. Before use, the soil was sieved (<2 mm) and used in the pot experiments described below.

2.1.2 Biochar Amendments

Standard Commercial Biochar This biochar is produced from raw wooden chips through gasification and pyrolysis at a CHP plant in a fixed-bed, multi-stage gasifier (GP750) (Brynda et al. 2020) with a heating time of 6 h between 500 and 600 °C. While the initial particle size distribution ranges from 0.5 to 10 mm (with 58.9% between 2 and 5 mm), for this study, the biochar was ground to a powder form with particles predominantly < 1 mm to ensure uniform mixing with soil. The biochar has a specific surface area of 350–700 m2/g, as determined by BET analysis.

MicroChar MicroChar represents a novel biochar product engineered for enhanced soil health and nutrient availability. It is produced through a multi-step process involving co-pyrolysis of biowaste and poultry droppings at temperatures between 400 and 600 °C, resulting in a stable carbon-rich matrix (comprising approximately 80% of the final product). Unlike conventional biochar, MicroChar directly incorporates beneficial microorganisms and organic nutrients into its structure. This is achieved by combining the pyrolyzed material with poultry manure dry matter (16% w/w), a bacterial consortium (1% w/w) consisting of *Rhizobium*, *Azotobacter*, *Pseudomonas*, and *Bacillus* species, and spores of arbuscular mycorrhizal fungi and *Trichoderma* (3% w/w). The mixture is then homogenized with a starch-based binder and granulated to a diameter of 3 mm. Following granulation, the MicroChar undergoes a final drying stage at a low temperature before storage. This process, detailed in patent No. 309,512 (Maroušek 2021), yields a granular product that is easily handled and applied in agricultural settings. The MicroChar has a specific surface area of 340.6554 m^2/g, as determined by BET analysis.

The soils and amendments were characterized for basic physico-chemical properties (Table 1). Total carbon and total nitrogen were determined using Formacs-SNC from Skalar. Samples of both soil and biochar were digested using the Mehlich 3 method, and total elemental concentrations of potassium (K), phosphorus (P), magnesium, sodium, sulfur (S), and calcium were measured using inductively coupled plasma optical emission spectrometry (ICP-OES, 720 ES, Varian Inc., CA, USA). The pH was measured using a pH meter 731, and electrical conductivity was determined using a Multimeter 3420. The standard hydrometer method calculated the bulk density and porosity (CEN ISO/TS 17892-4 2004, 2004).

Table 1 Physico-Chemical properties of the soils, biochar, and microchar used in this study

Parameter	Regosol Soil	Cambisol Soil	Biochar	MicroChar
pH	4.80	4.92	11.12	7.02
EC (µS.cm^{-1})	318	83	1400	1329
N_{tot} (g.kg^{-1})	0.54	0.50	5.8	9.88
C_{tot} (g.kg^{-1})	9.33	22.05	817	593
C/N	17.30	44.1	140	60
S_{tot} (g.kg^{-1})	0.24	0.22	0.34	0.035
P_{tot} (g.kg^{-1})	0.41	0.35	0.89	0.043
Ca_{tot} (g.kg^{-1})	1.10	1.32	16.4	0.025
Mg_{tot} (g.kg^{-1})	0.22	1.92	2.85	0.016
K_{tot} (g.kg^{-1})	8.49	22.24	3.9	0.045
Bulk density (g.cm^{-3})	1.49	1.10	/	/
Porosity (%)	41.1	43.5	/	/

2.2 Incubation Experiment

A short-term incubation experiment used a two-factorial design with four treatments: two soils and two amendment conditions (0% or 2% MicroChar, on a dry weight basis). The four treatments were: Regosol without amendment (R0%), Cambisol without amendment (F0%), Regosol with 2% MicroChar (RM2%), and Cambisol with 2% MicroChar (FM2%). The experiment was completed using 20 tubes (volume 50 mL), five replications per treatment, and filled with 60 g of soil. This experiment aimed to obtain a rapid overview of the mobility of N, P, and K in Cambisol and Regosol, both lacking organic matter and fertilizer.

Soil chemical analysis was conducted over 20 weeks, with a sampling of soil pore water once a week for six weeks, then twice a month from the seventh week, and finally once a month from the eleventh week until the end. Sampling was performed using Rhizon soil pore water samplers (Eijkelkamp Agrisearch equipment, NED) fixed to centrifuge test tubes. To maintain consistent moisture conditions, soil samples were stored in a closed box in a dark place to reduce sunlight exposure and minimize evaporation. Additionally, 20 ml of deionized water was added to each tube and allowed to settle for at least one hour before every pore-water sampling event (Dickens et al. 2007). Pore water was then evaluated for pH (pH meter 731 (WTW Germany), electrical conductivity (EC) (Multimeter 3420 (WTW Germany), total C and N concentrations (Vario MACRO CHN elemental analysis unit (CHNS Elementar Analytical Systems GmbH, Germany), dissolved organic carbon concentration (Total Organic Carbon analyser TOC-L a (CPH / CPN, Shimadzu), TNM-L segment flow analyser (Shimadzu), total nutrients (K, P, Mg, Na, S and Ca) concentrations (ICP-OES (720 ES, Varian Inc., CA, USA), and anions (nitrate (NO_3^-), phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}) concentrations (Dionex ICS-5000 ion chromatography system (Dionex, USA).

2.3 Pot Experiments

Two pot experiments were conducted in an air-conditioned greenhouse under controlled conditions (21 °C, 14 h light/10 h dark cycle) to investigate the effects of MicroChar on pea growth under drought stress. Regosol, a weakly developed, drought-prone soil with higher initial nutrient concentrations than Cambisol, was selected for these experiments due to its agricultural suitability. Specifically, Regosol exhibited significantly higher levels of dissolved phosphorus (0.98 mg/L for RM2% and 0.74 mg/L for FM2%), potassium (0.62 mg/L for RM2% and 0.45 mg/L for FM2%), and calcium (203.18 mg/L for both RM2% and FM2%) in soil pore water, as determined in a preliminary incubation experiment. Both experiments compared the effects of MicroChar against a control biochar treatment. In the first experiment, drought stress was imposed from week three onwards by withholding water from designated pots for two weeks. The second experiment aimed to evaluate the effects of late drought stress, and the timing of stress imposition will be detailed further in a subsequent section.

2.3.1 Pot Experiment 1

Experimental Design Five treatments were assessed: a control (CC) without additives and four treatments with the soil mixed with different amendments (Biochar (B), Hoagland (H), MicroChar, and MicroChar + Hoagland spiked. In each case, biochar and MicroChar were added at 2% (w/w) to 500 g of soil, and 100 mL of Hoagland solution was added to the designated treatments. The Hoagland treatment (H) and MicroChar + Hoagland treatment received 100 mL of a modified Hoagland nutrient solution (see Supplementary Table S1). Hoagland solution was prepared according to the method outlined by Hoagland and Arnon, as revised by Arnon and adapted from Asad (Asad et al. 2021; Hoagland and Arnon 1950). Hoagland was added to test the effectiveness of MicroChar with and without additional phosphorus. The mixtures were placed in 0.5 L pots, with 10 pots per treatment, further split into optimal conditions (5 pots) and drought conditions (5 pots). After mixture preparation, two germinated seeds of Pisum sativum L. were sown in each pot. The experiment followed a randomized design. Moisture sensors (FDR 5TM Decagon, USA) monitored soil moisture, and rhizon leaching tests were conducted weekly.

Water Regime: A preliminary field capacity test determined that 98.6 ml of water resulted in 80% (w/w). Based on this, and Sutuliene et al., on Pisum sativum L. (Sutuliene et al. 2022), a daily watering volume of 100 ± 1 mL

of deionized water was applied daily per pot for optimal conditions. The 63-day experiment included four watering phases: (i) Weeks 1–2: Daily watering at 100 ± 1 mL per pot for all treatments; (ii) Weeks 3–5: Stressed pots received 30 ± 1 mL/day (30% of optimal), while control pots continued at 100 ± 1 mL/day; (iii) Week 6: Drought stress intensified by withholding water from stressed pots; (iv) Weeks 7–8: Stressed pots returned to 100 ± 1 mL/day. (Brynda et al. 2020).

Soil and Plant Analysis Rhizon pore water sampling was conducted weekly to measure pH, EC, total C and N concentrations, and total nutrients and anions. The shoot length of pea plants was measured weekly. After 70 days, plants were harvested, weighed fresh, dried at 40 °C for two days and weighed again. Nutrient content was measured with ICP-OES after microwave-assisted acid digestion. The carbon and nitrogen content of the pea biomass was analyzed using Formacs-SNC from Skalar (Breda, the Netherlands).

2.3.2 Pot Experiment 2

An additional pot experiment was conducted to evaluate the stress response of plants further in this pot experiment. This subsequent pot experiment was necessary due to insufficient plant material available for leaf sampling in the initial pot experiment. The experimental setup, including treatments and pot arrangements, mirrored that of Pot Experiment 1. For detailed information regarding the experimental design, including the watering regime, please refer to the description provided for Pot Experiment 1.

Water Regime Specific modifications to the watering regime for this experiment are detailed below: Plants were initially watered daily with 30 mL of deionized water for four weeks. From week 5 onwards, drought stress was imposed by reducing watering to 12.5 mL/day for stressed pots. From week 7 onwards, stressed pots received 37.5 mL/day to simulate recovery..

Soil and Plant Analysis The soil chemical analysis was the same as in Pot Experiment 1. The growth of the peas was monitored and recorded weekly. Leaf sampling was done at three different stages of the experiment: before stress induction (week 7), during stress induction (weeks 8 and 9), and after plants were rehabilitated (week 10). At each collection, the last leaf, having completed its growth, was sampled, immediately frozen in liquid nitrogen, and stored (frozen) until further analysis. Before the analysis, leaves were lyophilized. Pigments were extracted from 5 mg of freeze-dried samples using 1 mL of acetone and centrifuged (microcentrifuge Sigma $1^{-1}4$, Germany) 5 min at 9000×g. The dry pigment mixtures obtained through evaporation under nitrogen were stored at -80 °C until analysis.

The presence of carotenoids, including neoxanthin, violaxanthin, antheraxanthin, lutein, zeaxanthin, and β-carotene, was detected using a HPLC-UV/VIS system consisting of Gradient Pump Beta, Autosampler HTA 300, Watrex Nucleosil 120-5-C18 column, Sapphire UV detector, and Vacuum Degasser DG 3014. The gradient solution consisted of acetonitrile/methanol/water (80:12:10) and methanol/ethylacetate (95:5) with 0.01% BHT, at a flow rate of 1 mL/min and a total analysis time of 25 min. Detection was performed at 445 nm. The HPLC system was calibrated with individual carotenoids at three concentrations, and quantification was performed using Clarity software expressed as µg/g DW. Tobacco leaves were used as the source for the carotenoid standards, which were purified through HPLC. Based on spectral parameters and absorption coefficients, carotenoids were identified and quantified by spectrophotometry.

After 13 weeks, plants were harvested; roots, shoots and pods were separated and weighed fresh and dry (after 2 days of drying at 40 °C and separation of peas from the pod). Nutrients were measured as described in the first pot experiment. Before analysis, leaves were lyophilized. Prior to analysis, the samples were dissolved in 200 µL of acetone.

2.4 Data Analysis

Data analysis was performed using multiple statistical software packages. The significance level for all analyses was set at $p < 0.05$.

Data Processing and Normality Normality of data was assessed using the Shapiro-Wilk test (SPSS v.29.0.0). Non-normal variables were transformed as follows: Box-Cox transformations ($\lambda = 0.5$) were applied to total nitrogen, calcium, magnesium, and sulfur (S). Johnson transformations were used for pH (SB family, $\lambda = 0.2$) and electrical conductivity (SU family, $\lambda = 0.3$). Phosphorus (P), potassium (K), and total organic carbon remained non-normal after transformation attempts and were subsequently analyzed using non-parametric methods.

Plant Biomass Plant biomass data (root, shoot, and pod dry weight) from both pot experiments were analyzed using two-way ANOVA with treatment and water condition as fixed factors and block as a random factor. Tukey's HSD post-hoc test was used for multiple comparisons. Temporal measurements of plant biomass were analyzed using mixed repeated measures ANOVA with treatment and water

condition as between-subjects factors, time as a within-subjects factor, and block as a random factor.

Soil Properties For the 20-week incubation experiment, soil pore-water chemistry was analyzed using mixed repeated measures ANOVA with treatment as a between-subjects factor, time as a within-subjects factor, and replication as a random factor. Soil properties from the pot experiments were analyzed using either two-way ANOVA with a general linear model for normally distributed data or Kruskal-Wallis tests with Bonferroni correction for non-normal data.

Multivariate Analyses Principal component analysis was performed on soil pore-water macronutrient data from the incubation experiment. Redundancy analysis was used to assess the relationships between explanatory variables (soil pore-water chemistry) and response variables (total biomass elemental concentrations) in pot experiment 1. Significance testing for the RDA was conducted using Monte Carlo permutation tests (999 permutations). Results are presented as means ± standard deviation for normally distributed data and medians (interquartile range: Q1-Q3) for non-normal data.

3 Results

3.1 Incubation Experiment

MicroChar addition significantly increased phosphorus concentrations in soil pore-water throughout the 20-week incubation period. This effect was more pronounced in Regosol (RM2%) than in Cambisol (FM2%). In week 1, phosphorus levels in RM2% were significantly higher (76.3 ± 20.0 mg.L^{-1}) compared to the Regosol control (4.4 ± 3.5 mg.L^{-1}) ($p < 0.05$). Similarly, FM2% showed significantly elevated phosphorus (11.1 ± 8.6 mg.L^{-1}) compared to the Cambisol control (0.5 ± 0.1 mg.L^{-1}) ($p < 0.05$). This trend persisted over the 20 weeks [report specific p-values for subsequent time points, if available; if not, state the overall significance of the trend across the 20 weeks]. While control phosphorus levels in Cambisol decreased from 0.5 ± 0.1 mg.L^{-1} in week 1 to 0.1 ± 0.1 mg.L^{-1} by week 20, and Regosol control levels fluctuated between 4.4 ± 3.5 mg.L^{-1} and 5.1 ± 1.5 mg.L^{-1}, RM2% maintained phosphorus levels between 42.5 and 60.4 mg.L^{-1}, and FM2% ranged from 2.6 to 5.4 mg.L^{-1}. Furthermore, MicroChar significantly altered soil nutrient dynamics, increasing nitrogen and potassium content, while decreasing carbon content (Fig. S1, S2 and S3; Table S2). Changes in pH and electrical conductivity were also observed. Principal component analysis revealed distinct clustering of MicroChar-amended soils, separate from control samples along the first principal component, indicating a significant modification of the overall soil chemistry profile driven by higher pore-water phosphorus, potassium, and dissolved organic carbon (Fig S1).

3.2 Pot Experiment 1

Soil moisture content in the control declined from 0.22 m^3m^{-3} to 0.12 m^3m^{-3} over eight weeks. Biochar amendment consistently increased soil moisture retention by 67% compared to the control (Fig. 1i). Under drought conditions, biochar-treated soil maintained higher moisture levels, while other treatments showed mixed results. During the recovery period, biochar exhibited the highest moisture increase (56%), followed by FB (23%), H (10%), and FB-S (3.13%) (Fig. 1ii).

Under optimal conditions, phosphorus concentration in control pore water decreased from 0.66 to 0.42 mg/L over nine weeks (Fig. 2). MicroChar treatments significantly increased soluble phosphorus levels by 320% and 415%, respectively, compared to the control. Under drought conditions, FB and FB-S amendments similarly enhanced phosphorus availability by 1358% and 774%, respectively (Fig. 2). MicroChar did not significantly affect pore water availability of nitrogen or potassium, which increased over time but showed no differences between treatments. Redundancy analysis indicated a positive association between MicroChar amendments, increased phosphorus availability, and greater plant biomass, suggesting that MicroChar-mediated phosphorus enhancement promoted plant growth (Fig. S4).

Under optimal watering, pea plants grown with MicroChar showed enhanced root and shoot mass compared to the control (Fig. 3a). However, under drought stress, no significant differences in root, shoot, or pod mass were observed between treatments (Fig. 3b). Furthermore, no treatment significantly affected the uptake of other measured nutrients (Table 2).

3.3 Pot Experiment 2

MicroChar significantly affected phosphorus availability in soil pore water under both optimal and drought conditions. While control levels peaked early and then declined by 52% by week 13, MicroChar treatments showed a substantial increase in phosphorus availability (1999%) between week 1 and 4, which was sustained, albeit at a lower rate, through week 13. The FB-S treatment (MicroChar + Hoagland solution) also enhanced phosphorus availability, peaking in week 3. Similar trends were observed under drought conditions, with both FB and FB-S treatments significantly increasing phosphorus availability, indicating MicroChar's effectiveness in enhancing nutrient retention under water stress.

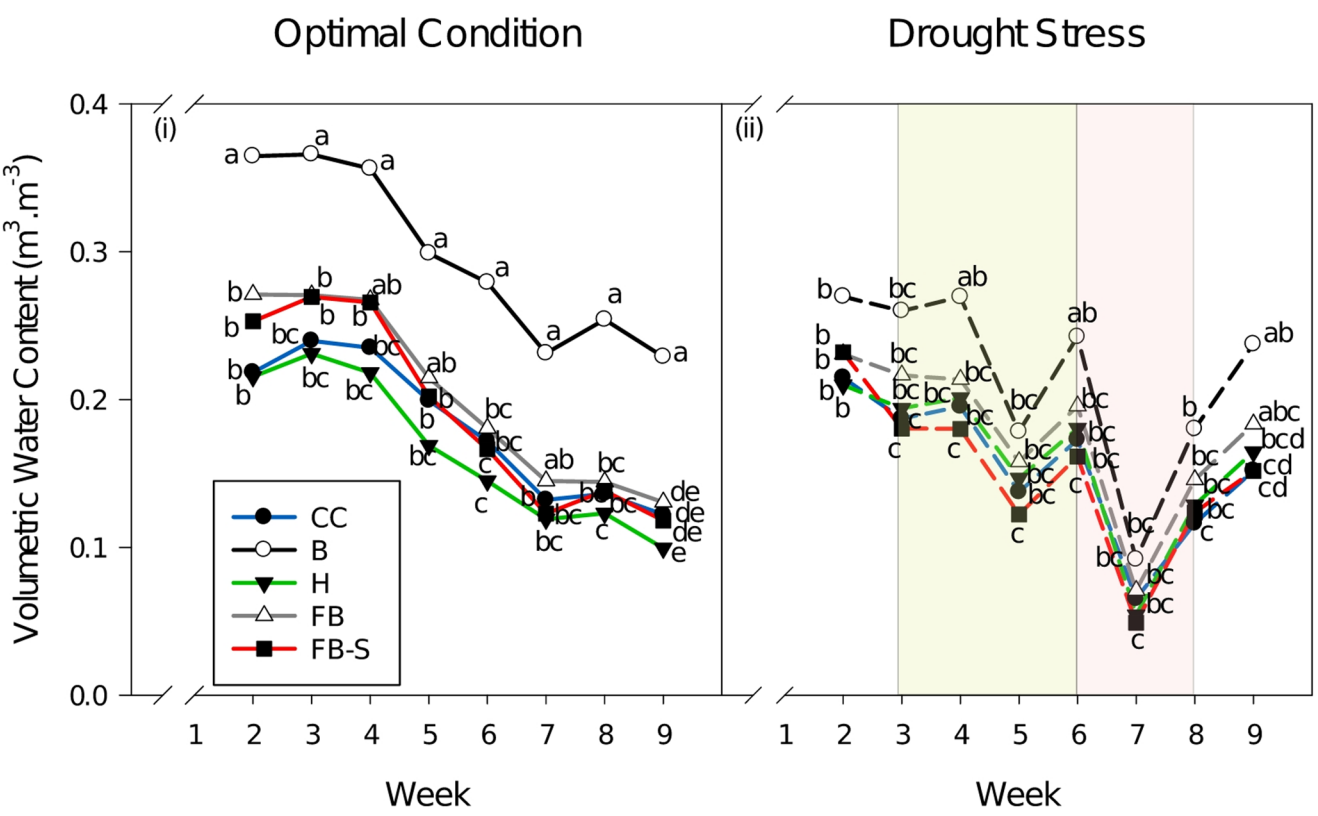


Fig. 1 Volumetric water content (m3 m-3) over 8 weeks in pots under (**i**) optimal moisture conditions and (**ii**) drought stress. Treatments: CC (non-amended soil), B (2% biochar), H (100 mL Hoagland solution), FB (2% MicroChar), and FB-S (2% MicroChar + 100 mL Hoagland solution). Drought stress: light yellow shading (weeks 3–6) indicates low stress; light red shading (weeks 6–8) indicates high stress. Data are means ($n = 5$). Different letters indicate significant differences between treatments within each week (Tukey test, $p < 0.05$))

MicroChar treatments also influenced plant physiological responses, particularly pigmentation. Under optimal conditions, both FB and FB-S maintained higher pigment levels, suggesting enhanced protection against drought-induced stress (Fig S6). However, these differences were less pronounced under drought conditions. Pod mass was not significantly affected by the treatments (Fig S5). Analysis of element content in pea pods revealed significant treatment effects. Under optimal conditions, phosphorus content in FB and FB-S treatments increased by 60% and 69%, respectively, compared to the control (2.66 g.kg^{-1}, Fig. 4b). Under drought conditions, FB showed a 44% increase compared to the control (3.37 g.kg^{-1}, Fig. 4b). Despite increased phosphorus uptake in pods, this did not translate into significantly higher pod mass.

4 Discussion

Unlike conventional biochar, MicroChar directly incorporates beneficial microorganisms and organic nutrients into its matrix (Maroušek 2021). This unique composition contributes to the observed increase in soluble phosphorus concentration in soil pore water following MicroChar addition, addressing concerns about phosphorus scarcity (Hafeez et al. 2017; Ulrich and Frossard 2014). Adding a small quantity of MicroChar led to an immediate and substantial increase in plant-available phosphorus in the soil pore water, to a greater degree than commercial biochar. Specifically, under optimal conditions, MicroChar treatments FB and FB-S elicited significant increases in soluble phosphorus levels compared to the control, enhancing it on average by 320% and 415%, respectively (Fig. 2). This increase aligns with observations by Fišarová et al. (Fišarová et al. 2024), who attributed improved P availability to MicroChar's microgranular structure, enhanced microbial activity, and synergistic effects with mycorrhizae. The positive effects of MicroChar on phosphorus availability is consistent with previous research on biochar (Dugdug et al. 2018; Luo et al. 2022; Yao et al. 2012). Furthermore, the enhanced phosphorus availability under drought conditions suggests that MicroChar could help maintain plant productivity and nutrient uptake during periods of water scarcity. However, while our study used Mehlich 3 for soil phosphorus analysis, this method may not fully elucidate the mechanisms by which MicroChar enhances phosphorus availability and warrants

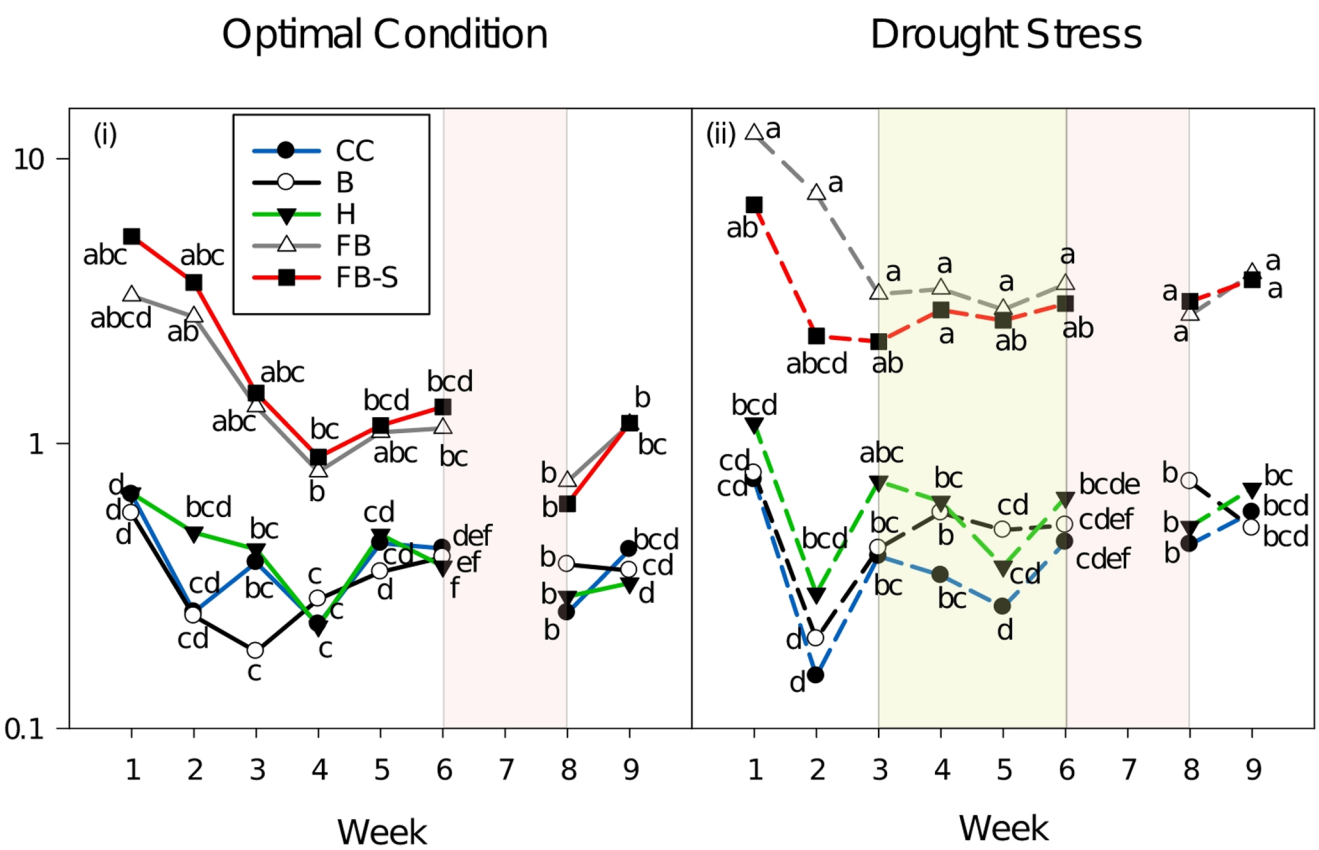


Fig. 2 Phosphorus concentration (mg L-1) in soil pore-water over 9 weeks under (**i**) optimal conditions and (**ii**) drought stress. Treatments: CC (non-amended soil), B (2% biochar), H (100 mL Hoagland solution), FB (2% MicroChar), and FB-S (2% MicroChar + 100 mL Hoagland solution). Drought stress: light yellow shading (weeks 3–6) indicates low stress; light red shading (weeks 6–8) indicates high stress. Pore-water collection paused during weeks 6–8 under optimal conditions. Data are means ($n = 5$). Different letters indicate significant differences between treatments within each week (Bonferroni test, $p < 0.05$)

further investigation using alternative methods (Pogorzelski et al. 2022; Reed et al. 2022).

Increasing phosphorus retention can minimize leaching losses from the root zone and help reduce eutrophication risks associated with phosphorus losses into waterways. (Dugdug et al. 2018). Determining the optimal application rates is essential to balance agronomic and environmental benefits and mitigate potential surface accumulation and erosion losses. Compared to commercial biochar, MicroChar is engineered to provide a slow release of phosphorus without affecting nutrients such as nitrogen, thus promoting inorganic phosphorus availability in the soil without disrupting the overall soil biogeochemistry (Dugdug et al. 2018).

It is important to acknowledge that despite significant increases in phosphorus availability, these did not consistently translate into proportional increases in biomass yield, especially under optimal conditions. In Pot Experiment 2, although the pod phosphorus content increased significantly under optimal and drought conditions with MicroChar, the implications of increased phosphorus content in plant tissues, such as potential toxicity or changes in nutrient balance, warrant further investigation (Carvalho et al. 2020). Our study also revealed differences in the magnitude of phosphorus increase between the two soil types tested. In the incubation experiment, the Cambisol, a more developed soil with higher organic matter content, exhibited a greater response to MicroChar amendments than the less developed Regosol. This suggests that soil properties, such as cation exchange capacity and buffering capacity, can influence the effectiveness of MicroChar in enhancing phosphorus availability (Schulz and Glaser 2012; Shayesteh Kheradmand & 2023). Therefore, defining optimal MicroChar application rates for different soil types will be crucial to maximize the agronomic and environmental benefits.

Adequate soil moisture is essential for maximizing the benefits of enhanced phosphorus availability, as water acts as the primary medium for nutrient transport to plant roots. Therefore, understanding MicroChar's influence on water retention is crucial for evaluating its overall impact on plant growth. However, the interaction between biochar and soil moisture is not straightforward, with factors like particle size significantly influencing the effects on water retention.

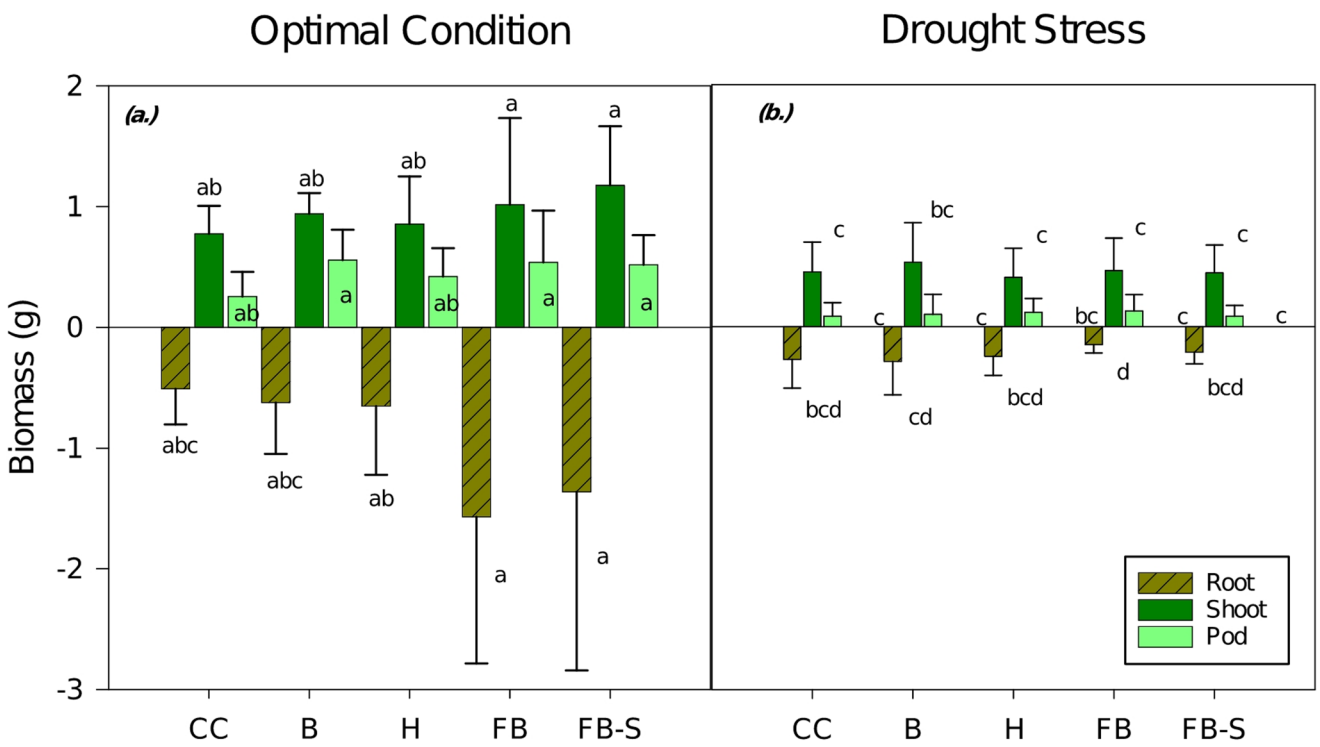


Fig. 3 Total biomass dry mass of *Pisum sativum* L in root, shoot, and pod from pot experiment one as a result of different treatments (CC = non-amended soil; B = soil amended with 2% (w/w) biochar; H = soil amended with 100 mL of Hoagland solution; FB = soil amended with 2% (w/w) MicroChar; FB-S = soil amended with 2% (w/w) MicroChar and 100 mL of Hoagland solution). Data is presented in means, and the letters signify a significant difference between treatments from Tukey test per week p-value < 0.05 ($n = 5$)

Table 2 Total element (carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur) concentrations ($g.kg^{-1}$) measured after 9 weeks in *Pisum sativum* L grown under the following treatments (CC = non-amended soil; b = soil amended with 2% (w/w) biochar; h = soil amended with 100 mL of hoagland solution; fb = soil amended with 2% (w/w) microchar; FB-S = soil amended with 2% (w/w) microchar and 100 mL of hoagland solution) under optimal (Opt.) and drought-stressed (DS) conditions. Letters indicate significant difference between all the treatments for both optimal and drought (p-value < 0.05, $n = 5$)

		Carbon ($g.kg^{-1}$)	Nitrogen ($g.kg^{-1}$)	Phosphorus ($g.kg^{-1}$)	Potassium ($g.kg^{-1}$)	Calcium ($g.kg^{-1}$)	Magnesium ($g.kg^{-1}$)	Sulfur ($g.kg^{-1}$)
Opt.	CC	320.14 ± 35.54 a	14.54 ± 2.37 a	1.91 ± 0.14 c	11.32 ± 2.28 a	8.42 ± 1.47 a	3.36 ± 0.34 a	4.51 ± 0.76 a
	B	303.70 ± 81.02 a	14.06 ± 2.63 a	1.80 ± 0.42 c	8.87 ± 2.62 a	7.12 ± 1.44 a	2.80 ± 0.50 ab	3.17 ± 0.83 ab
	H	285.06 ± 49.65 a	15.20 ± 2.25 a	1.98 ± 0.35 c	9.33 ± 3.42 a	7.77 ± 1.11 a	2.22 ± 0.26 b	3.14 ± 0.92 ab
	FB	361.90 ± 83.06 a	18.38 ± 7.35 a	1.92 ± 0.60 c	10.87 ± 1.29 a	8.44 ± 1.33 a	2.53 ± 0.38 ab	3.23 ± 0.66 ab
	FB-S	360.40 ± 8.28 a	18.10 ± 2.02 a	3.12 ± 0.28 a	11.19 ± 1.05 a	5.92 ± 0.70 a	2.91 ± 0.30 ab	3.17 ± 0.40 ab
DS	CC	347.86 ± 12.67 a	13.40 ± 3.60 a	1.83 ± 0.09 c	9.58 ± 1.05 a	7.75 ± 1.06 a	3.00 ± 0.32 ab	3.82 ± 0.97 ab
	B	320.38 ± 42.00 a	19.12 ± 2.76 a	1.94 ± 0.47 c	8.93 ± 3.03 a	8.88 ± 2.78 a	2.57 ± 0.52 ab	2.72 ± 0.45 b
	H	316.55 ± 93.12 a	12.63 ± 2.96 a	2.02 ± 0.50 c	11.64 ± 2.83 a	8.06 ± 0.71 a	2.74 ± 0.72 ab	3.40 ± 1.11 ab
	FB	318.42 ± 62.27 a	13.65 ± 3.81 a	2.18 ± 0.20 bc	10.29 ± 1.10 a	7.25 ± 1.01 a	2.77 ± 0.34 ab	3.70 ± 0.71 ab
	FB-S	375.30 ± 47.44 a	15.72 ± 1.73 a	2.81 ± 0.13 ab	9.75 ± 0.91 a	5.95 ± 1.11 a	2.67 ± 0.15 ab	2.82 ± 0.79 b

For example, biochar amendments have been shown to suppress water stress and improve sucrose content in sugar beet under certain conditions (Lebrun et al. 2022). Biochar can increase soil moisture content compared to the other amendments, under optimal and drought conditions (Lebrun et al. 2022). The high surface area and microporosity of biochar enable it to absorb and retain water through physiochemical mechanisms influenced by (Chen et al. 2023; Lebrun et al. 2024); biochar properties such as particle size and surface area distribution, aromaticity, and polarity (Mitchell et al. 2022). Tailoring biochar physical attributes, particularly particle size to soil conditions may help optimize moisture retention. This aligns with previous research showing biochar enhances soil water retention and plant drought tolerance (Bruun et al. 2022; Feng et al. 2023; Vitková et al. 2024). However, the relationship between biochar and particle size and water retention is complex. MicroChar particles are larger than typical biochar, around 1¯10 mm compared

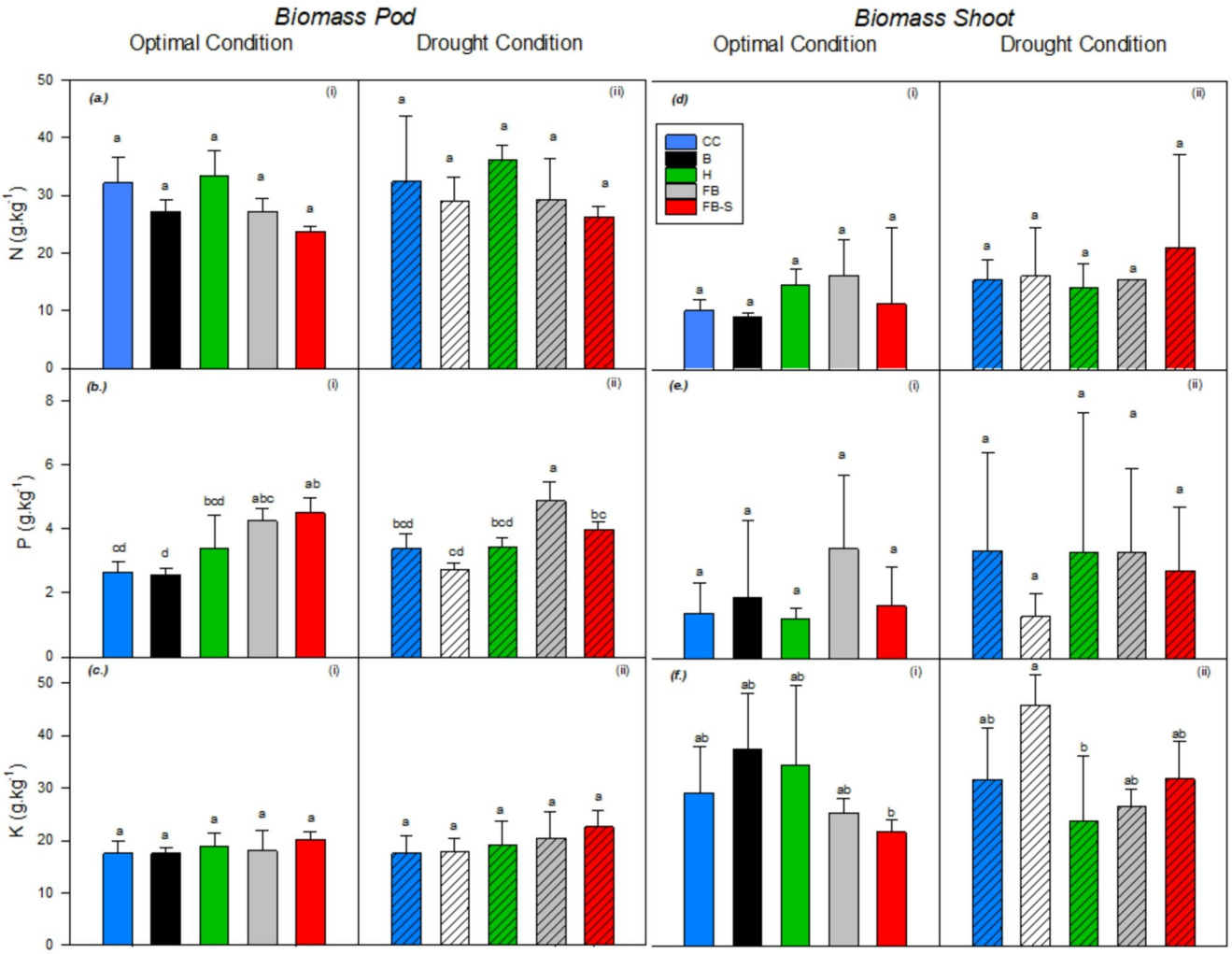


Fig. 4 Biomass total digest element content of *Pisum sativum* L grown in pots grown under optimal (**i**) and water-stressed conditions (**ii**). The following treatments were applied: CC = non-amended soil; B = soil amended with 2% (w/w) biochar; H = soil amended with 100 mL of Hoagland solution; FB = soil amended with 2% (w/w) MicroChar; FB-S = soil amended with 2% (w/w) MicroChar and 100 mL of Hoagland solution. The data is presented in means, and letters indicate Tukey test significant difference between treatments at a p-value < 0.05 ($n = 5$)

to < 1 mm for commercial biochar (Wang et al. 2019). The lower surface area of MicroChar particles likely reduces water holding capacity.

In this study, the commercial biochar, produced from raw wooden chips via gasification and pyrolysis (Brynda et al. 2020), had a wide particle size distribution, with a weighted average particle size of 1 mm. While this biochar was originally produced with larger particles (2–5 mm), it was ground to a powder form (< 1 mm) before soil application to ensure uniform mixing. In contrast, MicroChar, was specifically granulated to a diameter of 3 mm. This difference in particle size influenced their respective performance characteristics. The finely ground commercial biochar, with its smaller particles and consequently larger surface area per unit mass (Morales et al. 2013), demonstrated superior water-holding capacity, increasing soil moisture retention by 67% compared to the control. This enhanced moisture retention was particularly evident during the induced drought conditions and recovery period, where it showed the highest moisture increase (56%). Such improvements in water retention are particularly beneficial in sandy and low-clay soils, which are inherently prone to drought stress (Adekiya et al. 2020; Chen et al. 2020; Liu et al. 2017). While some experiments have shown mixed results regarding biochar's effect on water retention (Edeh and Mašek 2021; Ventura et al. 2012), our findings align with research indicating that finely ground biochar can significantly improve water retention in these soil types. Meanwhile, MicroChar's larger granular structure proved more effective for enhancing phosphorus availability, suggesting that different particle sizes can be tailored to optimize different soil improvement functions.

Different particle sizes can be tailored to optimize various soil improvement functions, including water retention. This enhanced water retention is crucial, especially under drought stress, as it directly impacts plant physiology by influencing nutrient uptake, utilization, and overall growth. discuss various aspects of plant responses to drought and rewatering. This section explores the physiological responses of pea plants to MicroChar application, focusing on phosphorus uptake under both optimal and drought conditions. Under optimal moisture conditions, MicroChar led to an increase in root, shoot, and pod biomass, possibly due to increased phosphorus availability. Conversely, commercial biochar had limited effects on plant growth under drought conditions. The redundancy analysis revealed phosphorus as the predominant driver of plant growth differences among treatments, rather than other soil nutrients like nitrogen or potassium. Despite increased phosphorus availability from MicroChar, plants could not fully utilize the additional phosphorus under drought stress, confirming previous findings on the interdependence of soil moisture and phosphorus for plant uptake (Tesfaye et al. 2021). This limitation underscores the importance of adequate soil moisture for realizing the benefits of enhanced phosphorus availability.

Compared to other amendments, MicroChar application resulted in higher phosphorus tissue concentration in the pea plants and helped maintain pigment levels through increased activity of DEAPS enzymes during drought stress, which efficiently dissipated excess light energy and protected the photosynthetic apparatus (Hafez et al. 2020). These findings highlight the significant impact of soil amendments on the physiological response of plants, particularly under stress conditions, as evidenced by the observed changes in pigmentation levels. Previous studies have also shown enzyme activity aids plant stress adaptation. Sutuliene (Sutuliene et al. 2023) showed antioxidant enzymes increased in pea plants under drought, likely mitigating oxidative stress. Enzymes regulating carbon and nitrogen metabolism also increased in drought-stressed peas (Sutuliene et al. 2022). By increasing phosphorus nutrition and enzyme activity, MicroChar may have helped maintain photosynthetic function and energy pathways under moisture deficit conditions. However, the extent to which these physiological benefits translate into overall biomass yield increases depends on the complex interplay of various nutrient dynamics within the soil, as discussed in the following section.

While these physiological benefits, particularly the enhanced phosphorus uptake, are promising, the overall impact of MicroChar on biomass yield depends on the complex interplay of nutrient dynamics within the soil. Building upon the observed physiological benefits of MicroChar, particularly its enhancement of phosphorus availability, requires consideration of the broader context of soil nutrient dynamics and their influence on overall biomass yield. One factor influencing our results is the potential sufficiency of existing nutrient availability in the soil used in these experiments to meet the plants' nutritional requirements, thus limiting the potential for additional growth responses. In other words, when soil nutrient levels are adequate, further fertilization does not necessarily yield proportional increases in biomass (Tripolskaja and Asakaviciute 2019). Additionally, plant growth is often limited by factors other than nutrient availability, such as genetic potential or environmental factors such as light and CO_2 availability, which play critical roles in photosynthesis and overall plant health (Ertuş et al. 2023). The complex interactions between macronutrients, particularly N, P, and K, also influence plant responses to individual nutrient additions. Specifically, an imbalance in these nutrients can lead to suboptimal growth, as plants require a specific ratio of these macronutrients for optimal physiological functioning (Basu et al. 2021).

While MicroChar significantly augments phosphorus availability and uptake, its effects on other nutrients like nitrogen and potassium are less pronounced. This element-specific effect can likely be attributed to the following: the chemistry of phosphorus, characterised by a high affinity for mineral surfaces in soil, makes it particularly responsive to addition of high surface area materials like MicroChar (Bulgakova et al. 2023). Moreover, the microorganisms present in MicroChar may possess specific phosphorus-solubilizing capabilities, enhancing phosphorus availability without similarly affecting other nutrients (Tsvetkov 2024). Lastly, initial soil conditions, including the relative abundance of different nutrients before amendment, may have influenced the observed effects, with phosphorus often being a limiting factor in agricultural contexts (Basu 2023).

Beyond the immediate effects on nutrient availability and plant growth, the application of MicroChar presents broader environmental implications related to soil health, resource use, and climate change mitigation. The environmental implications of MicroChar application extend beyond direct crop productivity effects. Our findings demonstrated a significant increase in soil pH from acidic (4.429–4.580) to a more neutral range (5.864–6.495), potentially reducing lime requirements in acidic soils. The enhanced phosphorus availability (18.298 mg/kg under drought, 25.755 mg/kg under optimal conditions) indicates potential for reducing phosphate fertilizer applications by 20–25% (Liu et al. 2024; Y. Wang et al. 2023a, b). This efficiency gain aligns with findings from similar biochar studies (Zhang et al. 2023) and addresses growing concerns about phosphorus resource depletion.

MicroChar's performance under drought conditions and improved water retention suggests potential for climate

change adaptation in agricultural systems. Studies with similar biochar formulations have shown 10–15% increases in water-holding capacity(Guan et al. 2023; Wang et al. 2023a, b). The stable organic matter content of MicroChar contributes to carbon sequestration through both direct carbon storage in its aromatic structure and enhanced soil organic matter accumulation (Oriaku et al. 2023; Zheng 2024). Recent meta-analyses of biochar applications suggest potential carbon sequestration rates of 0.3–0.7 tons C/ha/year in similar soil types (Neenu et al. 2023; Wu et al. 2024).

The successful implementation of MicroChar in agricultural systems requires careful consideration of practical aspects. Our study demonstrated effectiveness at 2% w/w application rate, supporting findings from similar studies (Wigan 2023). Integration with existing agricultural practices requires specific adjustments based on enhanced nutrient availability. Recent field trials with similar products suggest the possibility of reducing conventional phosphate fertilizer applications by 20–25% (Gupta 2024; Qing-sheng et al. 2024), while maintaining crop productivity. Irrigation modifications should account for improved water retention, with studies indicating potential 10–15% reductions in irrigation frequency under similar conditions (Martinez et al. 2023).

5 Conclusion

Our study demonstrates that using MicroChar, either alone or in conjunction with other soil amendments, effectively releases required nutrients in nutrient-leached soil while mitigating leaching, enhancing sustainability and economic feasibility. Moreover, our findings reveal the element-specific efficacy of soil amendments, emphasizing the importance of tailored nutrient management. Additionally, different amendments exhibit varying effects on plant pigmentation and chlorophyll levels, highlighting their potential to influence plant physiology. These findings contribute to the knowledge on sustainable agriculture practices and have implications for optimizing nutrient management, improving soil health, and maximizing crop productivity while minimizing environmental impacts.

The use of MicroChar as a soil amendment shows promise as a strategy to improve phosphorus availability in nutrient-depleted soils. MicroChar may promote more efficient phosphorus cycling and boost phosphorus nutrition in crops by enhancing soluble phosphorus levels in the soil pore water. However, the degree of plant growth response is mediated by moisture availability. Overall, targeted use of MicroChar to sustainably increase phosphorus availability in agricultural systems holds potential to enhance phosphorus use efficiency, reduce reliance on inorganic fertilizers, and aid in overcoming the global phosphorus challenge.

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Declarations

Conflict of Interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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References

Adekiya AO, Agbede TM, Olayanju A, Ejue WS, Adekanye TA, Adenusi TT, Ayeni JF (2020) Effect of Biochar on soil properties, soil loss, and Cocoyam yield on a tropical sandy loam Alfisol. ScientificWorldJournal 2020(9391630):Article. https://doi.org/10.1155/2020/9391630

Akinnuoye-Adelabu DB, Steenhuisen S, Bredenhand E (2019) Improving pea quality with vermicompost tea and aqueous biochar: Prospects for sustainable farming in Southern Africa [Article]. South African Journal of Botany, 123, 278–285, Article. https://doi.org/10.1016/j.sajb.2019.03.009

Asad S, He PB, He PF, Li YM, Wu YX, Ahmed A, Wang YY, Munir S, He YQ (2021) Interactions between Indigenous endophyte<i>bacillus subtilis L1-21 and nutrients inside Citrus in reducing Huanglongbing pathogen<i>candidatus liberibacter Asiaticus. Pathogens, 10, Article 1304 https://doi.org/10.3390/pathogens10101304

Basu S (2023) Diversity and traits of multiple biotic stressors elicit differential defense responses in legumes. Agriculture 13(2093). https://doi.org/10.3390/agriculture13112093. Article

Basu S, Clark RE, Bera S, Casteel CL, Crowder DW (2021) Responses of Pea Plants to Multiple Antagonists Are Mediated by Order of Attack and Phytohormone Crosstalk. Molecular Ecology, 30, 4939–4948, Article. https://doi.org/10.1111/mec.16103

Bruun E, Müller-Stöver D, Pedersen BN, Hansen LV, Petersen C (2022) Ash and Biochar amendment of coarse sandy soil for growing crops under drought conditions. Soil Use Manag 38:1280–1292. https://doi.org/10.1111/sum.12783. Article

Brynda J, Skoblia S, Pohorely M, Beno Z, Soukup K, Jeremias M, Mosko J, Zach B, Trakal L, Syc M, Svoboda K (2020) Wood chips gasification in a fixed-bed multi-stage gasifier for decentralized high-efficiency CHP and Biochar production: Long-term commercial operation. Fuel 281 Article 118637. https://doi.org/10.1016/j.fuel.2020.118637

Bulgakova VS, Shatskaya NV, Kosterin OE, Vasiliev GV (2023) Cases of paternal inheritance and recombination of mitochondrial DNA in peas (Pisum L). Euphytica, 219, Article https://doi.org/10.1007/s10681-023-03207-z

Carvalho ML, Moraes MTd, Cerri CEP, Cherubin MR (2020) Biochar amendment enhances water retention in a tropical sandy soil. Agriculture 10(62). https://doi.org/10.3390/agriculture10030062. Article

Castellini M, Diacono M, Gattullo CE, Stellacci AM (2021) Sustainable Agriculture and Soil Conservation. Applied Sciences-Basel, 11, Article 4146. https://doi.org/10.3390/app11094146

Chen Z, Chen C, Kamchoom V, Chen R (2020) Gas permeability and water retention of a repacked silty sand amended with different particle sizes of peanut shell Biochar. Soil Sci Soc Am J 84:1630–1641. https://doi.org/10.1002/SAJ2.20130. Article

Chen X, Li L, Li X, Kang J, Xia X, Shi H, Ren X (2023) Effect of Biochar on Soil-Water characteristics of soils: A Pore-Scale study. Water, 15, 1909, Article https://doi.org/10.3390/w15101909

Dickens GR, Koelling M, Smith DC, Schnieders L (2007) Rhizon sampling of pore waters on scientific drilling expeditions: an example from the IODP expedition 302, Arctic coring expedition (ACEX). https://doi.org/10.2204/iodp.sd.4.08.2007. Scientific Drilling, Article

Dugdug AA, Chang SX, Ok YS, Rajapaksha AU, Anyia A (2018) Phosphorus sorption capacity of biochars varies with biochar type and salinity level. Environmental Science and Pollution Research, 25, 25799–25812, Article. https://doi.org/10.1007/S11356-018-1368-9/TABLES/4

Edeh I, Mašek O (2021) The role of Biochar particle size and hydrophobicity in improving soil hydraulic properties. https://doi.org/10.5194/EGUSPHERE-EGU21-4117. EGU21, Article

Ertuş MM, Bezirganoglu I, Yazıcılar B (2023) Access to genetic diversity in cultivated forage pea (Pisum sativum var. Arvense L.) genotypes through SSR markers. https://doi.org/10.21203/rs.3.rs-2480717/v1. Article

Feng W, Wang T, Yang F, Cen R, Liao H, Qu Z (2023) Effects of Biochar on soil evaporation and moisture content and the associated mechanisms. Environ Sci Europe 35:1–12. https://doi.org/10.1186/S12302-023-00776-7/FIGURES/9. Article

Fišarová L, Berchová K, Lukáč M, Beesley L, Vosátka M, Hausenblas M, Trakal L (2024) Microgranular Biochar improves soil fertility and mycorrhization in crop systems. Soil Use Manag 40:e13068–e13068. https://doi.org/10.1111/SUM.13068. Article

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

Guan TK, Wang Q, Li J, Yan H, Chen Q, Sun J, Liu G, Han Y, Zou Y, Zhang G (2023) Biochar immobilized plant Growth-Promoting rhizobacteria enhanced the physicochemical properties, agronomic characters and microbial communities during lettuce seedling. Front Microbiol 14., Article. https://doi.org/10.3389/fmicb.2023.1218205

Gupta RK (2024) Biochar Influences Nitrogen and Phosphorus Dynamics in Two Texturally Different Soils. Scientific Reports, 14, Article. https://doi.org/10.1038/s41598-024-55527-2

Hafeez Y, Iqbal S, Jabeen K, Shahzad S, Jahan S, Rasul F, Effect of biochar application on seed germination and seedling growth of glycine max (L (2017).) Merr. Under drought stress [Article]. Pak J Bot 49:7–13 Article://WOS:000404235800002

Hafez Y, Attia K, Alamery S, Ghazy A, Al-Doss A, Ibrahim E, Rashwan E, El-Maghraby L, Awad A, Abdelaal K (2020) Beneficial effects of Biochar and Chitosan on antioxidative capacity, osmolytes accumulation, and anatomical characters of Water-Stressed barley plants. Agronomy-Basel, 10, Article 630 https://doi.org/10.3390/agronomy10050630

Hoagland D, Arnon D (1950) The water culture method for growing plants without soil. Calif Agri Exp Stat Circ 347:1–32., Article. https://cir.nii.ac.jp/crid/1571698600870392320

Kammann CI, Linsel S, Gossling JW, Koyro HW (2011) Influence of biochar on drought tolerance of Chenopodium quinoa Willd and on soil-plant relations [Article]. Plant and Soil, 345, 195–210, Article. https://doi.org/10.1007/s11104-011-0771-5

Lebrun M, Boucek J, Bimova KB, Kraus K, Haisel D, Kulhanek M, Omara-Ojungu C, Seyedsadr S, Beesley L, Soudek P, Petrova S, Pohorely M, Trakal L (2022) Biochar [article]n manure [article] an suppress water stress of sugar beet (Beta vulgaris) and [article] ncrease sucrose [article]ontent [article]n [article]ubers [Article]. Sci Total Environ 814(10)., Article 152772. https://doi.org/10.1016/j.scitotenv.2021.152772

Lebrun M, Aguinaga MA, Zahid Z, Šimek P, Ouředníček P, Klápště P, Száková J, Berchová-Bímová K, Jačka L, Beesley L, Punčochář J, Trakal L (2024) Manure-biochar blends effectively reduce nutrient leaching and increase water retention in a sandy, agricultural soil: insights from a field experiment. Soil Use Manag 40., Article. https://doi.org/10.1111/sum.13135

Lin WW, Lin MH, Zhou HY, Wu HM, Li ZW, Lin WX (2019) The effects of chemical and organic fertilizer usage on rhizosphere soil in tea orchards. PLoS ONE 14 e0217018, Article e0217018. https://doi.org/10.1371/journal.pone.0217018

Liu Z, Dugan B, Masiello CA, Gonnermann HM (2017) Biochar particle size, shape, and porosity act together to influence soil water properties. PLoS One, 12, e0179079, Article. https://doi.org/10.1371/journal.pone.0179079

Liu M, Zhang S, Wang X (2024) Mechanisms of phosphorus retention and release in biochar-modified soils. J Environ Manage 301:114–128 Article

Luo D, Wang L, Nan H, Cao Y, Wang H, Kumar TV, Wang C (2022) Phosphorus adsorption by functionalized biochar: a review. Environmental Chemistry Letters 2022 21:1, 21, 497–524, Article. https://doi.org/10.1007/S10311-022-01519-5

Madadgar S, AghaKouchak A, Farahmand A, Davis SJ (2017) Probabilistic estimates of drought impacts on agricultural production [Article]. Geophysical Research Letters, 44, 7799–7807, Article. https://doi.org/10.1002/2017gl073606

Maroušek J (2021) Číslo spisu: PV 2021–592. Article. https://isdv.upv.gov.cz/webapp/!resdb.pta.frm

Maroušek J, Strunecký O, Stehel V (2019) Biochar farming: defining economically perspective applications. Clean technologies and environmental policy, vol 21. Springer, pp 1389–1395

Martinez RL, Johnson RM, Davis ME (2023) Irrigation management in biochar-amended soils: Field-based evidence. Agricultural Water Management, 270, 107–119, Article

Mitchell K, Beesley L, Šípek V, Trakal L (2022) Biochar and its potential to increase water, trace element, and nutrient retention in soils. Biochar Agric Achiev Sustainable Dev Goals 25–33. https://doi.org/10.1016/B978-0-323-85343-9.00008-2. Article

Morales MM, Comerford N, Guerrini IA, Falcão NPS, Reeves JB (2013) Sorption and desorption of phosphate on Biochar and Biochar–soil mixtures. Soil Use Manag 29:306–314. https://doi.org/10.1111/SUM.12047. Article

Neenu S, Gopal M, Gupta A, Bhat R, Apshara SE (2023) Understanding the dynamics of phosphorus sorption in acidic soil amended with cocoa pod husk Biochar. J Plantation Crops 153–160. https://doi.org/10.25081/jpc.2023.v51.i3.8927. Article

Nguyen TTN, Xu CY, Tahmasbian I, Che R, Xu Z, Zhou X, Wallace HM, Bai SH (2017) Effects of Biochar on soil available inorganic nitrogen: A review and meta-analysis. Geoderma 288:79–96. https://doi.org/10.1016/J.GEODERMA.2016.11.004. Article

Oriaku JC, Mong OO, Onyeocha CE, Kalu P, Ndubuisi CO, Srinivasan GR, Onwukwe IE (2023) Experimental study of Biochar production process using a pilot carbonization kiln as a biofuel's properties improvement module. Asian J Environ Ecol 22:133–140. https://doi.org/10.9734/ajee/2023/v22i3498. Article

Page KL, Dang YP, Dalal RC (2020) The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. Front Sustainable Food Syst 4:31. https://doi.org/10.3389/fsufs.2020.00031

Pogorzelski D, Santos WO, Pimentel GG, Matias PC, Vergütz L, Ballotin FC (2022) Do We Properly Quantify P From Mehlich 1 or Mehlich 3 Extracting Solutions? Article. https://doi.org/10.21203/rs.3.rs-2022830/v1

Qing-sheng XU, Du L, Deng R (2024) Using machine learning to predict Biochar yield and carbon content: enhancing efficiency and sustainability in biomass conversion. BioResources 19:6545–6558. https://doi.org/10.15376/biores.19.3.6545-6558. Article

Reed V, Finch B, Souza JLB, Watkins P, Arnall DB (2022) Soil sampling depth impact on phosphorus yield response prediction in winter wheat. Agricultural Environ Lett 7:Article. https://doi.org/10.1002/ael2.20067

Schmidt HP, Kammann C, Hagemann N, Leifeld J, Bucheli TD, Sanchez-Monedero MA, Cayuela ML (2021) Biochar in agriculture - A systematic review of 26 global meta-analyses. Global Change Biology Bioenergy 13:1708–1730. https://doi.org/10.1111/gcbb.12889. Article

Schulz H, Glaser B (2012) Effects of Biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. J Plant Nutr Soil Sci 175:410–422. https://doi.org/10.1002/jpln.201100143. Article

Shayesteh Kheradmand SM (2023) Synergistic effects of Biochar and phosphorus fertilization on wheat growth, pollution reduction, and soil enzymatic behavior. J Genetic Eng Biotechnol Res 5:153–161. https://doi.org/10.33140/jgebr.05.03.02. Article

Sutuliene R, Rageliene L, Samuoliene G, Brazaityte A, Urbutis M, Miliauskiene J (2022) The response of antioxidant system of Drought-Stressed green pea (Pisum sativum L.) affected by watering and foliar spray with silica nanoparticles. Horticulturae 8:35. https://doi.org/10.3390/horticulturae8010035

Sutuliene R, Brazaityte A, Malek S, Jasik M, Samuoliene G (2023) Response of oxidative stress and antioxidant system in pea plants exposed to drought and Boron nanoparticles. Antioxidants 12:528. https://doi.org/10.3390/antiox12020528

Tesfaye F, Liu X, Zheng J, Cheng K, Bian R, Zhang X, Li L, Drosos M, Joseph S, Pan G (2021) Could biochar amendment be a tool to improve soil availability and plant uptake of phosphorus? A meta-analysis of published experiments. Environmental Science and Pollution Research 2021 28:26, 28, 34108–34120, Article. https://doi.org/10.1007/S11356-021-14119-7

Toreti A, Bavera D, Acosta Navarro J, Cammalleri C, de Jager A, Di Ciollo C, Essenfelder H, Maetens A, Magni W, Masante D, Mazzeschi D, Niemeyer M, S., Spinoni J (2022) Drought in Europe August 2022. In *Publications Office of the European Union, Luxembourg*

Tramblay Y, Koutroulis A, Samaniego L, Vicente-Serrano SM, Volaire F, Boone A, Le Page M, Llasat MC, Albergel C, Burak S, Cailleret M, Kalin KC, Davi H, Dupuy JL, Greve P, Grillakis M, Hanich L, Jarlan L, Martin-StPaul N, Polcher J (2020) Challenges for drought assessment in the Mediterranean region under future climate scenarios. In *Earth-Science Reviews* (Vol. 210): Elsevier B.V

Tripolskaja L, Asakaviciute R (2019) Effects of fertilisers on pulse crop productivity and nitrogen assimilation on acid soil. Plant Soil Environ 65:536–540. https://doi.org/10.17221/462/2019-pse. Article

Tsvetkov M (2024) Pyrolysis of Laminaria Japonica with Biochar production and its characteristics. E3s Web Conferences 474(01012). https://doi.org/10.1051/e3sconf/202447401012. Article

Ulrich AE, Frossard E (2014) On the history of a reoccurring concept: phosphorus scarcity. Sci Total Environ 490:694–707. https://doi.org/10.1016/J.SCITOTENV.2014.04.050. Article

Ventura F, Salvatorelli F, Piana S, Pieri L, Pisa PR (2012) The effects of biochar on the physical properties of bare soil. Earth and Environmental Science Transactions of The Royal Society of Edinburgh, 103, 5–11, Article. https://doi.org/10.1017/S1755691012000059

Verheijen F, Jeffery S, Bastos AC, Van Der Velde M, Diafas I (2010) *Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions* (9789279142932). (Environment, Issue. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Biochar+Application+to+Soils+A+Critical+Scientific+Review+of+Effects+on+Soil+Properties,+Processes+and+Functions#0

Vitková J, Šurda P, Lichner Ľ, Výleta R (2024) Influence of Biochar application rate, particle size, and pyrolysis temperature on hydrophysical parameters of sandy soil. Appl Sci 14(3472). https://doi.org/10.3390/app14083472. Article

Walan P, Davidsson S, Johansson S, Hook M (2014) Phosphate rock production and depletion: regional disaggregated modeling and global implications. Resour Conserv Recycling 93:178–187. https://doi.org/10.1016/j.resconrec.2014.10.011. Article

Wang JY, Xiong ZQ, Kuzyakov Y (2016) Biochar stability in soil: meta-analysis of decomposition and priming effects [Review]. Global Change Biology Bioenergy, 8, 512–523, Article. https://doi.org/10.1111/gcbb.12266

Wang DY, Li CY, Parikh SJ, Scow KM (2019) Impact of biochar on water retention of two agricultural soils - A multi-scale analysis [Article]. Geoderma, 340, 185–191, Article. https://doi.org/10.1016/j.geoderma.2019.01.012

Wang C, Zheng M, Feng Y, Zhang S, Zhang Y, Liu F, Chen L, Song Q, Yang X, Gao W, Li Z (2023a) Effects of Biochar-Based fertilizer on soil physicochemical properties and rhizosphere bacterial community structure. Pnssi 2., Article. https://doi.org/10.23977/pnssi.2023.020101

Wang Y, Liu J, Lu X (2023b) Enhanced phosphorus availability in biochar-amended agricultural soils: A meta-analysis. Soil Biology and Biochemistry, 176, 108–121, Article

Wigan MB (2023) Impact of Biochar application on chemical and microbial properties of soil. Int J Multidisciplinary Appl Bus Educ Res 4:2503–2510. https://doi.org/10.11594/ijmaber.04.07.27. Article

Wu X, Quan W, Chen Q, Gong W, Wang A (2024) Efficient adsorption of nitrogen and phosphorus in wastewater by Biochar. Molecules, 29, 1005, Article https://doi.org/10.3390/molecules29051005

Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR (2012) Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere, 89, 1467–1471, Article. https://doi.org/10.1016/J.CHEMOSPHERE.2012.06.002

Zhang H, Chen Y, Li T (2023) Biochar effects on soil phosphorus transformation and crop uptake: A systematic review. Agriculture, Ecosystems & Environment, 338, 108–119, Article

Zheng X (2024) Identifying Life Cycle Environmental Hotspots in Phosphorus Recovery From Wastewater Using Modified Biochars. Acs Sustainable Chemistry & Engineering, 12, 17319–17327, Article. https://doi.org/10.1021/acssuschemeng.4c07048

Zhou Q, Houge BA, Tong Z, Gao B, Liu G (2018) An in-situ technique for producing Low-Cost agricultural Biochar. Pedosphere 28:690–695. https://doi.org/10.1016/S1002-0160(17)60482-X. Article

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