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Hydrochars as slow-release phosphorus fertilizers for enhancing corn and soybean growth in an agricultural soil

Anahita Khosravi¹, Yanfei Yuan², Qiang Liu², Hao Zheng^{2,3*}, Masoud Hashemi¹, Yuanzhi Tang⁴ and Baoshan Xing^{1*} 

Abstract

Hydrochars as carbonaceous amendments rich in porous structures and nutrients can be used as promising slow-release fertilizers and soil health amendments. Yet, the performance of hydrochars derived from different feedstocks in improving crop plant growth and soil phosphorus (P) availability is not well understood. Here, a batch of sewage sludge (SS) and chicken manure (CM) derived hydrochars (SSCs and CMCs) were produced at 125 and 225 °C (SS125/225 and CM125/225) to investigate their characteristics and performances in improving the seedling growth of two representative crops, soybean (*Glycine max*) and corn (*Zea mays*), as well as the P availability in an acidic agricultural soil in comparison with triple super phosphate (TSP), a conventional P fertilizer. Compared with CMCs, SSCs with more porous and rougher surfaces contained relatively lower contents of carbon (C; 32.3–33.3%), hydrogen (H; 3.9–4.69%), and potassium (K; 29.2–51 mg g⁻¹), but higher contents of P (37.4–85.4%) and nitrogen (N; 2.26–4.9%), as well as more O-containing and N-containing functional groups. The impacts of hydrochars on soybean and corn growth showed distinct variations. The application of SSCs showed little effect on soybean growth (i.e., biomass, chlorophyll contents, and number of leaves), while CMCs significantly increased its total dry biomass by 23.2–66.2%. For corn, both SSCs and CMCs increased the total dry biomass by 32.8–92.4% and 21.8–69.7%, respectively, compared to those in the un-amended soils. In addition, compared with the higher temperature hydrochars (SS225 and CM225), the lower temperature ones (SS125 and CM125) increased the total dry biomass by 24.6% and 34.9% for soybean and 44.8% and 39.3% for corn, respectively. The significant improvement in crop growth by hydrochars was mainly due to the direct nutrient supply (particularly P) by the hydrochars, which was supported by the increased soil and shoot P concentrations. Moreover, hydrochar application led to a rise in soil water soluble P (WSP) levels. However, as time progressed, these levels fell due to the fixation and adsorption of P via precipitation, electrostatic attraction, and ion exchange on the hydrochars. Contrarily, TSP maintained persistently high soil WSP levels, increasing the leaching risk of P through the soil profile. Our results provide direct evidence for hydrochars as slow-release P fertilizers to enhance crop growth and production and give better insights for producing functionalized P-rich chars as an alternative to chemical P fertilizers to maintain sustainable agricultural production.

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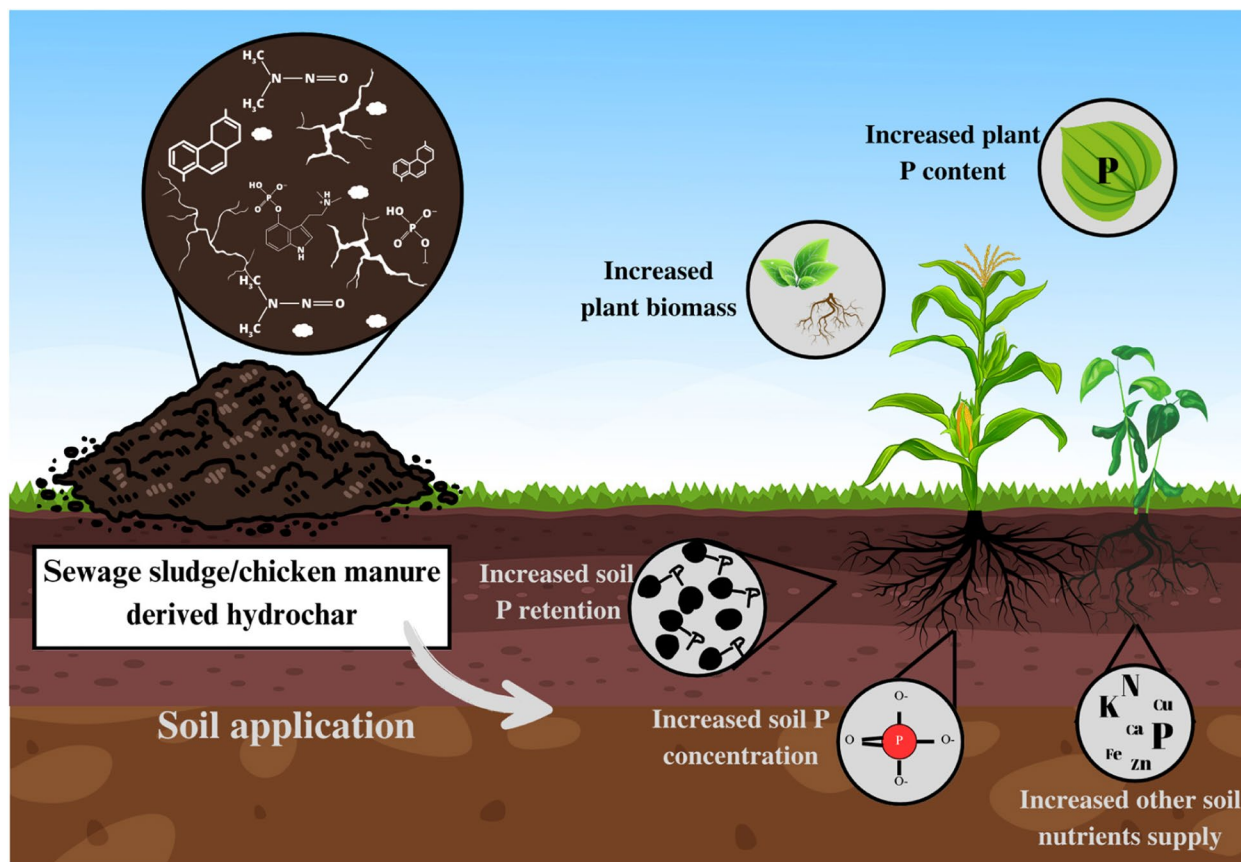
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Highlights

- Sewage sludge derived hydrochars (SSCs) with richer porous had higher P and N contents than chicken manure hydrochars (CMCs).
- Soil amended with SSCs and CMCs increased corn growth but only CMCs enhanced soybean growth.
- Both SSCs and CMCs increased shoot P uptake of corn and soybean, while they mitigated soil P leaching via adsorption.

Keywords Hydrothermal carbonization, Sewage sludge, Chicken manure, Phosphorus availability, Leaching

Graphical Abstract



1 Introduction

Soil degradation has recently gained global attention since healthy soils play important roles in sustainable agricultural production, food security, water quality, climate change and human health (Lehmann et al. 2020). Soils generally are overexploited and degraded due to poor managements, such as deforestation, overgrazing, over-cultivations, and over-fertilization (Ferreira et al. 2022). Soil degradation includes the loss of soil physical, chemical and biological qualities via erosion, salinization/sodification, acidification, pollution, and compaction. It

results in the depletion of 36–75 billion metric tons of global lands annually, and causes low fertility, productivity, and biodiversity of global soil ecosystems (Gobinath et al. 2022). Soil degradation also leads to loss of soil organic carbon (SOC) by surface runoff and decomposition, thus further aggravating soil degradation and global climate change (Borrelli et al. 2017). It has been reported that shifting the natural habitats to agricultural ecosystems will result in the loss of SOC by up to 51% in the U.S. by year 2100 (Gautam et al. 2022) and 35% in Europe (Lugato et al. 2018). A report estimated that 20–80 tons

carbon (C) ha^{-1} of the global SOC is annually emitted to the atmosphere due to SOC depletion (Lal 2004; Song et al. 2022). In addition, the degradation of 75 billion tons of soil annually results in 50% reduction in agricultural production and an annual cost of US\$ 400 billion globally (Maximilian et al. 2019). Therefore, the development of sustainable and economical approaches to remediate the degraded soils and to improve soil health is urgently needed.

So far, many strategies for restoring SOC pools and improving soil health have been proposed, such as cover crops, fertilization, improved grazing, no-till agriculture, fallow, forestation, irrigation, and amendment application (Lehmann et al. 2020; Song et al. 2022; Yuan et al. 2023; Liu et al. 2023b). Among them, one of the most convenient approaches is the direct application of soil amendments, such as biowaste, composts, and chars (Zheng et al. 2020). Char materials such as biochar and hydrochar derived from thermochemical treatment of biomass wastes, are characterized with high carbon/nutrient contents, high porosity, surface area, and active functional groups (Golia et al. 2022; Yin et al. 2021; Shikha et al. 2023), and are considered as promising amendments due to their significant effects on improving soil physical, chemical and biological properties (Khosravi et al. 2021; Golia et al. 2022; Zheng et al. 2018; Yuan et al. 2023). Compared to biochar, hydrochar derived from hydrothermal carbonization (HTC) has been considered as a preferable amendment for soil and plant health due to the following reasons. First, HTC operated at milder temperatures (180–375 °C) with rapid conversion rates may energy-efficiently convert high-moisture biomass (>30%) like sewage sludge and kitchen wastes into solid hydrochar, avoiding the extra energy input for pre-drying and heating at a higher temperature (up to 700 °C) during pyrolysis for biochar (Khosravi et al. 2021; Fang et al. 2018; Lee et al. 2020). Second, HTC may retain a greater proportion of the original nutrients from the feedstock in hydrochar than biochar, in which the majority of N is removed as gas phase during pyrolysis (Khosravi et al. 2021; Fang et al. 2018). Last, the physicochemical properties of hydrochar marked by a unique combination of aliphatic and aromatic structures rich in surface oxygen-containing functional groups render it more hydrophilic than biochar (Kumar et al. 2020; Khosravi et al. 2021; Zheng et al. 2020). Hydrochar may be a propitious resolution to global aggressive soil degradation and low crop production (Khosravi et al. 2021). Studies have evidenced that hydrochar could improve soil physical properties such as aggregate stability, porosity, bulk density, and water holding capacity (Kalderis et al. 2019), optimize soil chemical properties such as pH, cation exchange capacity (CEC), and electrical conductivity (EC) (Khosravi

et al. 2021), and regulate microbial community (Sun et al. 2020) and plant growth (McIntosh et al. 2022). These recent studies mainly focus on the hydrochar characteristics derived from various feedstocks and HTC conditions (Ghanim et al. 2018; Ma et al. 2021), the two dominant factors controlling hydrochar characteristics and performances in soils (Kumar et al. 2020; Luutu et al. 2022). So far, the effects of hydrochar application on plant production have been studied on barley (Bargmann et al. 2013), leek (Bargmann et al. 2014), beans (Melo et al. 2018), mastic and myrtle (Belda et al. 2016), alfalfa (George et al. 2012), and lettuce (Mau et al. 2020). However, these studies showed inconsistent performance (i.e., positive, negative, or no effects) of hydrochars as soil amendments on plant growth (Melo et al. 2019; de Jager and Giani 2021; Luutu et al. 2022). Thus, uncertainties remain regarding the effects of feedstock type and hydrothermal treatment conditions on hydrochar properties in terms of nutrient availability and performance in improving plant growth.

The enhanced plant growth in soils amended with hydrochars can be ascribed to the direct benefits as a slow-release fertilizer (Melo et al. 2018; Zhao et al. 2018) and indirect benefits such as enhanced nutrient/water retention and improved soil properties (Fei et al. 2019a; de Jager and Giani 2021). Hydrochars are generally rich in plant essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K) (Fei et al. 2019b; Khosravi et al. 2021). Among them, P received little attention in terms of its roles in plant growth (Chu et al. 2020; Yu et al. 2019). This lack of focus is concerning, given the declining availability of P minerals for fertilizer production worldwide (Tonini et al. 2019), the persistent issues concerning P in soils such as its low plant availability and accessibility, and its tendency to bind with other elements, causing soil eutrophication and water quality degradation, both of which pose significant challenges to sustainable agriculture (Liu et al. 2023a; Eltohamy et al. 2023). Hydrochar may also affect soil P biogeochemical cycling, such as sorption, desorption, leaching, and mineralization (Huang et al. 2018; Huang and Tang 2015). The majority of these studies regarding P fertilization potential mainly focused on hydrochars derived from sewage sludge (McIntosh et al. 2022). P in sewage sludge is primarily present as inorganic P, particularly in the form of orthophosphate ions and polyphosphates (Huang and Tang 2015), whereas animal manures contain both inorganic (e.g., orthophosphate) and organic P (e.g., phytic acids; Huang et al. 2017). However, there is a very limited knowledge regarding the potential in P fertilization potential for hydrochars derived from different feedstocks, which might differ in carbon and nutrient speciation, composition, and surface/pore characteristics.

In the present study, the sewage sludge (SS) and chicken manure (CM) derived hydrochars (SSCs and CMCs) were produced at 125 and 225 °C to study their physicochemical properties and roles in improving the growth of soybean (*Glycine max*) and corn (*Zea mays*) in an agricultural soil using pot and column greenhouse experiments. Both SS and CM are globally produced in vast quantities (e.g., 4.5 million dry metric tons of SS and 1.4 billion metric tons of CM in the U.S. (EPA, 2020; Pagliari et al. 2020), and their rich contents of essential nutrients offer a unique opportunity for resource reutilization. Converting SS and CM into hydrochars may harness their nutrient potential for prolonged fertilization, presenting an environmentally friendly approach for waste management. In addition, corn and soybean are two globally important crops with an annual production of 359 million and 1148 million metric tons, respectively (Bittencourt et al. 2021; Wang et al. 2021b). The U.S. Midwest Corn Belt produces over 33% of the world's corn and 34% of the world's soybeans (Wang et al. 2020b). We hypothesize that hydrochars derived from SS and CM with improved P fertilization potential will increase soil P availability to boost plant growth, and this enhancement would be different based on the hydrochar feedstock and HTC temperatures (HTT). Accordingly, the specific objectives of this study were to: 1) compare the physical-chemical properties of hydrochars derived from SS and CM at different HTT of 125 and 225 °C; 2) determine the growth response of corn and soybean in an agricultural soil amended with the hydrochars, and 3) examine P availability of hydrochars and retention in the soil amended with the hydrochars in comparison with triple super phosphate (TSP), a conventional P fertilizer. The findings can provide fundamental information for evaluating the potential of sewage sludge and chicken manure derived hydrochars as slow-release fertilizers on P availability in soils and shedding light for the design and selection of high efficiency fertilizers for sustainable agriculture.

2 Materials and methods

2.1 Soil sampling

Field soil was collected from the surface horizon (0–30 cm) of the University of Massachusetts Agricultural Experiment Station Farm (42°28'37" N, 72°36'2" W) in South Deerfield, MA. The farm field has been cultivated with corn (*Zea mays*) during the past 5 years and was kept fallow for 3 months before the sampling. Soil samples were randomly collected from six different sites in the field, mixed, air-dried, ground, and passed through a 2-mm sieve. The soil was classified as a fine sandy loam (60% sand, 32% silt and 8% clay) with a pH of 4.7, CEC of 7.6 meq 100 g⁻¹, bulk density of 1.4 g cm⁻³, total C of

2.3%, total N of 0.18%, C/N ratio of 12.7, and exchangeable P, K, calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu) contents of 11.4, 50, 95, 15, 5, 17, 0.8, and 0.3 mg kg⁻¹, respectively. All the soil samples were amended with 0.2% (w/w) limestone (CaCO₃) before planting the seeds as recommended by the University of Massachusetts soils laboratory for pH correction (6.5).

2.2 Preparation of hydrochars

Sewage sludge (SS) and chicken manure (CM) were selected as feedstocks to produce hydrochars (SSCs and CMCs) at 125 and 225 °C as described by our previous studies (Wang et al. 2020a; Wang et al. 2021a; Zhang et al. 2021). These biowastes containing large amounts of N and P were selected since they are produced in tremendous amounts globally, leading to severe biowaste management challenges. The temperature of 125 °C and 225 °C was selected based on our previous studies (Wang et al. 2020a; Wang et al. 2021a; Zhang et al. 2021). At 125 °C, the bioavailable P and enhanced ammonia bioavailability in the hydrochars were observed, while more stable P (strengite) was observed at 225 °C. Additionally, energy efficiency was also considered for the heating temperature selection. Briefly, the SS was collected from the F. Wayne Hill Water Resources Center (Buford, GA, USA), and centrifuged to 10% dry mass (i.e., solid/liquid ratio of 1/9 (w/w)) in the lab. The chicken manure was collected from a farm at the University of Georgia (Athens, GA, USA), and then mixed with deionized water to achieve a solid-liquid ratio of 1/9 (w/w). Then 90 g SS or CM suspension was loaded into a 200-mL high-pressure chemical reactor (CIT-HiPR-ST100 Model, COL-INT TECH., SC, USA). The reactor was heated in an oven at 125 or 225 °C for 4 h (including 3 h ramping and 1 h holding time at the target temperature). After heating, the reactor was naturally cooled down to room temperature. The slurries were separated into solids as hydrochars and processed water by centrifugation. Note that the treatment at 125 °C did not fully convert biomass to hydrochars and resulted in little process water, but the solids were still regarded as hydrochars in this study. Thereafter, SSCs and CMCs produced at 125 and 225 °C were labeled as SS125, SS225, CM125, and CM225, respectively. All the hydrochars were dried to a constant weight in the oven at 60 °C and stored in room temperature for further experiments.

2.3 Characterization of hydrochars

Total C, N, H, and oxygen (O) contents of the hydrochars and feedstocks were measured using an ECS 4010 CHNS-O elemental analyzer (Costech Analytical Technologies, USA). pH was measured at a ratio of 1:10 (w/v)

in deionized water using an electronic pH meter (Fisher scientific model XL 200). Total contents of macronutrients (P, K, Ca, Mg) and micronutrients (Fe, Mn, Zn, Cu) were extracted by the digestion in concentrated nitric acid. A 2030 inductively coupled plasma mass spectrometry (ICP-MS, Shimadzu, Kyoto, Japan) was used to measure the contents of K, Ca, Mg, Fe, Mn, Zn, and Cu. Total P content was calorimetrically measured by ammonium molybdate-ascorbic acid method using an ultraviolet–visible spectroscopy (UV-vis, Agilent 8453, Santa Clara, USA; Murphy and Riley 1962). Surface functional groups were measured using a Fourier Transform Infrared Spectroscopy spectrophotometer equipped with a universal Attenuated Total Reflection sampling accessory (ATR-FTIR, PerkinElmer, USA). Transmission spectra were scanned from 4000 to 500 cm⁻¹ at a resolution of 4 cm⁻¹ using KBr pellets at room temperature. Surface morphology of the hydrochars were characterized by FEI Magella 400 XHR scanning electron microscopy (SEM, S-4800, Hitachi, Japan). The transformation and speciation of P in the feedstock and their derived hydrochars have been fully reported in our previous studies (Huang et al. 2018; Wang et al. 2021a; Huang and Tang 2016), and the selected results are provided in the *Supplementary Information* (Table S1).

2.4 Pot experiments

Two pot experiments were carried out under greenhouse conditions (day: 25 °C; night: 20 °C; relative humidity 74%; light period 16/8, day/night) in Spring 2021 at the University of Massachusetts, Amherst. Plastic pots (15 cm in height and 12 cm in diameter) with holes at the bottom were used and plastic trays were placed under each pot for irrigation. The following eight treatments were

included: (i) 1000 g soil without any amendments as control treatment (CK); (ii) 998.8 g soil + 1.2 g sewage sludge (SS); (iii) 997.9 g soil + 2.1 g SS125 (SS125); (iv) 999 g soil + 0.93 g SS225 (SS225); (v) 996.3 g soil + 3.7 g chicken manure (CM); (vi) 996.6 soil + 3.4 g CM125 (CM125); (vii) 997.2 g soil + 2.8 g CM225 (CM225); and (viii) 996 g soil + 4 g triple super phosphate (Ca(H₂PO₄)₂, TSP). All the pots were placed with a factorial arrangement in a completely randomized design with four replications. Since total P concentrations in all the hydrochars and feedstock were different (Table 1), they were added at different rates to achieve the same target P dosage of 80 mg P kg⁻¹ soil. Following dosage guidelines established in previous studies (McIntosh et al. 2022), we aimed to effectively balance agricultural productivity and environmental sustainability. By adhering to these recognized standards, our research contributes to and aligns with the broader scientific discourse on hydrochar use in agriculture. TSP was selected due to its high P solubility (20 g L⁻¹ at 25 °C and a pH 7) and wide global application as a fast release P fertilizer. The air-dried soils were mixed thoroughly with the desired amount of hydrochar or feedstock and transferred to the pots. Subsequently, three corn (*Zea Mays* L.) seeds or two soybean (*Glycine max* L.) seeds were planted within the top 1.5 cm of soils in each pot and thinned to one seedling after germination. Soil moisture was maintained at 65% of the maximum water holding capacity (WHC) to prevent any nutrient leaching by adding distilled water. Plant shoots and roots were harvested after 45 days of cultivation, when the collar of eighth leaf in corn and third trifoliolate in soybean were visible. At harvest time, the chlorophyll content (by Soil Plant Analysis Development (SPAD) meter, Konica Minolta, Osaka, Japan), leave number and plant height

Table 1 Characteristics of sewage sludge, chicken manure, and their derived hydrochars

| | SS ^a | SS125 | SS225 | CM | CM125 | CM225 |
|-----------------|---------------------|---------|---------|---------|---------|---------|
| C (%) | 31.7 b ^β | 32.3 b | 33.3 b | 35.1 b | 35.4 b | 41.4 a |
| H (%) | 5.63 a | 4.69 ab | 3.90 b | 4.83 ab | 4.62 ab | 3.87 b |
| O (%) | 29.4 ab | 16.2 bc | 14.3 c | 32.1 a | 21.1 b | 19.2 b |
| N (%) | 6.31 a | 4.90 b | 2.26 c | 2.67 c | 3.71 bc | 3.36 bc |
| C/N | 5.27 c | 6.46 c | 14.29 a | 13.3 a | 9.46 b | 12.3 ab |
| H/C | 2.13 a | 1.74 a | 1.40 a | 1.65 a | 1.56 a | 1.12 a |
| O/C | 0.69 a | 0.38 a | 0.33 a | 0.68 a | 0.45 a | 0.34 a |
| (O+N)/C | 1.03 a | 0.64 b | 0.44 b | 0.81 ab | 0.63 b | 0.48 b |
| Ash content (%) | 19.1 a | 19.4 a | 19.8 a | 13.2 b | 14.4 b | 15.8 b |
| pH | 5.74 a | 5.56 a | 5.64 a | 5.80 a | 5.61 a | 5.46 a |

^a SS sewage sludge, CM chicken manure, SS125 and SS225 sewage sludge derived hydrochar produced at 125 and 225 °C, CM125 and CM225 chicken manure derived hydrochar produced at 125 and 225 °C

^β Different lowercase letters after the numbers indicate significant differences between different hydrochars and feedstock, which were analyzed by Duncan's New Multiple Range Test at p < 0.05 using SAS statistical software (9.1.3, the SAS Inst., Cary, NC).

were measured. The dry weights of roots (RDW) and shoots (SDW) were recorded. Meanwhile, the soil was collected, air dried and passed through a 2-mm sieve. Total contents of macronutrients (P, K, Ca, and Mg) and micronutrients (Fe, Mn, Zn, and Cu) in the shoots were extracted by a digestion method using concentrated nitric acid (de Jager and Giani 2021). Modified Morgan extraction method was used to extract exchangeable P, K, Ca, Mg, Fe, Mn, Zn and Cu in the soils (McIntosh 1969). Briefly, 4 g soil, 0.5 g activated carbon and 20 mL modified Morgan solution (0.62 N NH_4OH + 1.25 N CH_3COOH) were added to a 50 mL centrifuge flask and were shaken at 120 rpm for 15 minutes. The supernatant was passed through grade 5 Whatman filter papers (pore size of 2.5 μm) and the contents of K, Ca, Mg, Fe, Mn, Zn, and Cu were measured using the same ICP-MS (Shimadzu, Kyoto, Japan). Also, soil exchangeable P content (SPC) was calorimetrically measured by ammonium molybdate–ascorbic acid method using UV-vis spectrophotometer (UV-vis, Agilent 8453, Santa Clara, USA).

2.5 Soil column experiment

In order to investigate the effects of hydrochars on soil P retention, two batches of soil column experiments were conducted using polyvinylchloride (PVC) pots with 20 cm in height and 8 cm in internal diameter. The columns were divided into four sections of 5 cm length each (0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm) to study the migration of water soluble P (WSP) in the soils amended with different hydrochars. These columns can be filled with 4 kg soil, hence each section contained 1 kg soil. During the packing, all the pots were first filled with 3 kg soil, then another 1 kg soil-hydrochar mixture was added to the pots as the topsoil. The treatments included: 1000 g soil without any amendments as control (CK); (ii) 998.8 g soil + 1.2 g sewage sludge (SS); (iii) 997.9 g soil + 2.1 g SS125 (SS125); (iv) 999 g soil + 0.93 g SS225 (SS225); (v) 996.3 g soil + 3.7 g chicken manure (CM); (vi) 996.6 g soil + 3.4 g CM125 (CM125); (vii) 997.2 g soil + 2.8 g CM225 (CM225); and (viii) 996 g soil + 4 g TSP. Each treatment was prepared in eight replicates. After preparation of all the columns, deionized water was added to the soil to reach 65% of maximum WHC, and the moisture was maintained consistent throughout the whole experiment (Fig. S1). Greenhouse conditions (day: 25°C; night: 20°C; relative humidity 74%; light period 16/8 h, day/night) were kept consistent throughout the experiment. After 1 month, soil samples from one batch of the columns (four replicates of each treatment) at different depths (0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm) were collected and air dried for further analysis. The second batch of columns (four replicates of each treatment) were cultivated in the same conditions for 6 months, and then the

soil samples were collected at different depths (0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm) and air dried. After all the soil samples were air dried, WSP contents were measured using ammonium molybdate–ascorbic acid method via UV-vis (Murphy and Riley 1962; Huang et al. 2018).

2.6 Statistical analysis

All the data were subjected to statistical analyses by analysis of variance (ANOVA). Means were compared by Duncan's New Multiple Range Test at 5% level of significance using SAS statistical software (SAS, 9.1.3, The SAS Inst., Cary, NC). Pearson correlation analysis was performed by RStudio (4.1.2.) software with the Corrplot package.

3 Results and discussion

3.1 Characteristics of the hydrochars

3.1.1 Elemental compositions

Elemental analysis showed that HTC increased C content but decreased O and H contents in SSCs and CMCs compared to their corresponding feedstocks (Table 1). SS125 and SS225 had relatively equivalent C contents (32.3–33.3%), while CM225 had significantly higher C content (41.1%) than CM125 (35.4%). The higher C contents in the hydrochars compared with the feedstocks were ascribed to the C enrichment induced by aromatization, condensation and carbonization (de Jager et al. 2022). The C contents in CMCs were higher than in SSCs (Table 1), in agreement with previous studies (Li et al. 2018; You et al. 2022), indicating that feedstock type plays important roles in determining the C contents of hydrochars. Feedstocks with higher aromatic C contents (e.g., xylose) generally result in higher C contents in their derived hydrochars (Li et al. 2018). Consistently, HTC at 225°C decreased the H and O content of SS225 by 16.8% and 11.7% compared to SS125 (Table 1), mainly due to decarboxylation and dehydration (Nguyen et al. 2022). A similar trend was also observed for CMCs, showing higher H contents than SSCs, mainly due to the hydrolysis of fructose in CM and production of hydrophilic groups such as hydroxyl and carboxyl groups (Nguyen et al. 2022). In addition, O contents of SSCs were lower than those of CMCs, showing higher volatile matter content in SS (Zhou et al. 2020). Consistently, a significant increase in the C/N ratio of the SSCs relative to the pristine SS reflected the high degree of carbonization and aromatization of the hydrochars (You et al. 2022).

3.1.2 Nutrients contents

Ash content, an important indicator of nutrient levels in chars (Zheng et al. 2013; Kambo et al. 2018), was relatively stable at 19.1–19.8% for SS and SSCs, 13.2–15.8% for CM and CMCs (Table 1). The total contents of P, Ca,

Mg, Fe, and Mn increased in both SSCs and CMCs relative to the feedstocks, while K and Na contents showed decreasing trends (Fig. 1, Table 1). The mineral composition and C content of feedstock generally determine the ash contents of hydrochars (Li et al. 2018). Feedstocks like CM rich in non-soluble minerals calcium phosphates and silicates, generally result in relatively high ash contents in their derived hydrochars with increasing HTT (Khosravi et al. 2021). HTC showed obvious decreasing effects on the total N contents (TN) of the hydrochars (Table 1). TN content in SS225 significantly decreased by 53.8% compared to SS125, while TN contents in CM125 and CMC225 remained stable at 3.36–3.71% (Table 1). The variation in TN contents among these hydrochars can be attributed to the different types of feedstocks. Feedstocks such as SS containing high amounts of inorganic N may undergo hydration during HTC, leading to N removal by both liquid and gaseous phases (Zhuang et al. 2017; Aragón-Briceño et al. 2021). For lignocellulosic feedstocks like CM, organic N such as proteins and nucleic acids can go through peptide bond cleavage, deamination, and ring opening, leading to the production and stabilization of NO_3^- -N, NH_4^+ -N, and NO_2^- -N (Zhuang et al. 2017; Khosravi et al. 2021). This is why higher N content was observed in CM125 compared to CM. As HTT increased from 125 to 225 °C, P content decreased in SS125 and then significantly increased in

SS225 relative to SS (Fig. 1A). In addition, SSCs showed higher P contents than CMCs due to the higher P content in SS (64.3 mg g^{-1}) relative to CM (21.1 mg g^{-1}). The relatively high amounts of organic P in SS was decomposed and solubilized in the gaseous/liquid phase as HTT reached 125 °C (Table S1). As HTT increased to 225 °C, a proportion of organic P was hydrolyzed and transformed to inorganic P, which may explain the higher content of P in SS225. In addition, the increased P content in CMCs was also due to P stabilization with other elements such as Ca, Mg, Fe and Al (Huang et al. 2018), which is consistent with the increased contents of Ca, Mg and Fe in the hydrochars with increasing HTT (Fig. 1C-E). Conversely, K contents of SSCs and CMCs exhibited decreasing trends as HTT increased (Fig. 1B), mainly attributed to high solubility of K during HTC process (Su et al. 2021). Previous studies demonstrated that feedstocks such as straw, paper sludge, and CM containing high levels of water-soluble alkali metals (e.g., K and Na) could undergo significant removal of these elements due to the presence of subcritical water during HTC (Su et al. 2021). Biochars typically exhibit relatively lower available nutrient contents compared to hydrochars, especially in terms of P and N contents (Yin et al. 2022). For instance, P content ranges from 1.6 to 20 mg g^{-1} and 4.4 to 59 mg g^{-1} in biochars derived from crop residues and animal wastes, respectively (Marcinićzyk and Oleszczuk

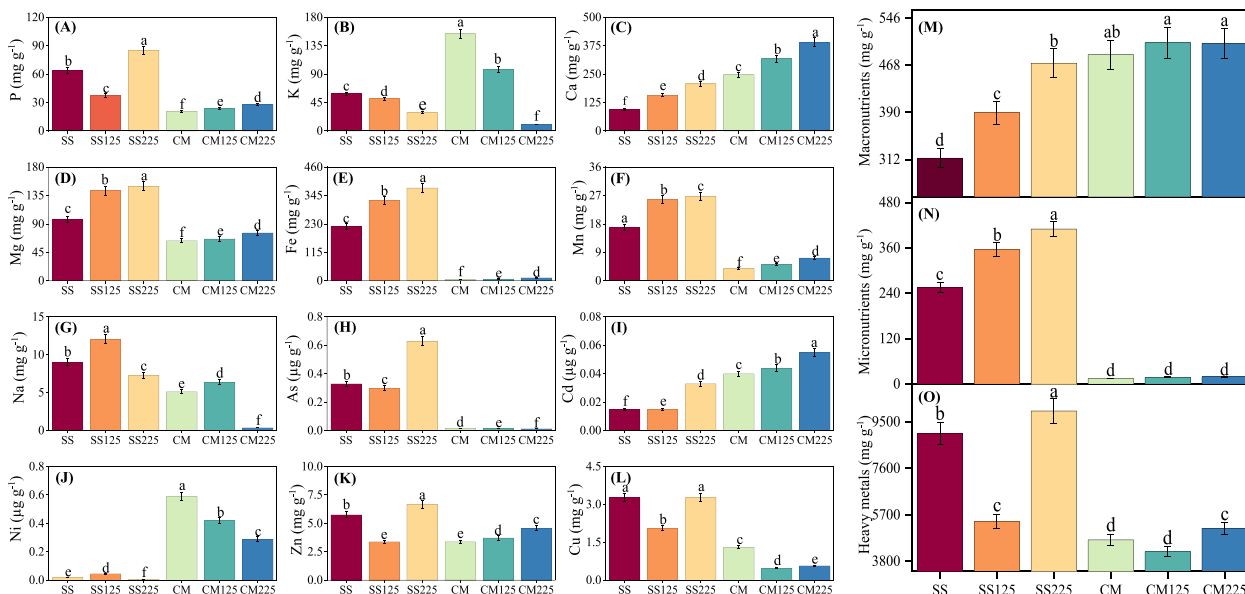


Fig. 1 The contents of individual macronutrients (P, K, Ca, and Mg) (A-D), micronutrients (Fe, Mn, and Na) (E-G) and heavy metals (As, Cd, Ni, Zn, and Cu) (H-L), as well as the summation of all the tested macronutrients (M), micronutrients (N) and heavy metals (O) in the sewage sludge and chicken manure derived hydrochars. SS: sewage sludge; CM: chicken manure; SS125 and SS225: sewage sludge derived hydrochar produced at 125 and 225 °C; CM125 and CM225: chicken manure derived hydrochar produced at 125 and 225 °C. Different lowercase letters on the bars indicate significant differences between different hydrochars and feedstock, which were analyzed by Duncan's New Multiple Range Test at $p < 0.05$ using SAS statistical software (9.1.3, the SAS Inst., Cary, NC)

2022), considerably lower than those in the SSCs (37.4–85.4 mg g⁻¹) and CMCs (23.6–27.9 mg g⁻¹).

Notably, the contents of heavy metals including As, Cd, Ni, Zn and Cu in the hydrochars varied (Fig. 1H–L). Their total concentrations followed the decreasing patterns of Zn > Cu >> As > Ni > Cd > Pb in SSCs and, Zn > Cu >> Ni > Cd > As > Pb in CMCs. These can be attributed to the inherent characteristics of the feedstocks and the varying effects of HTC on metal dissolution and precipitation, where a fraction of heavy metals can be chelated with the functional groups (e.g., carboxyl and hydroxyl groups) and the rest can be transformed into liquid phase (Lee and Park 2021; Hu et al. 2015). It is important to evaluate the heavy metal contents in hydrochars according to the established standards to ensure their safe application in agriculture. The International Biochar Initiative (IBI) has set specific guidelines for biochar, which can also serve as a reference for hydrochar (IBI 2015). Compared to these standards for the heavy metals (As, Cd, Ni, Zn, and Cu), their contents in our hydrochars were all lower than those of the threshold values, because our feedstocks came from the low-contamination areas. However, HTC might both decrease or enrich heavy metals in hydrochars (Leghari et al. 2023; Lu et al. 2022; Alipour et al. 2021), which should be considered before the application.

3.1.3 Surface morphology and chemical structure of hydrochars

The SEM images showed the distinguished morphologies of SSCs and CMCs (Fig. 2). Flat, non-porous, dense, and amorphous structures were observed on SS (Fig. 2A, B), whereas these flat surfaces disappeared in SSCs, and rougher surfaces with cracks developed in SSCs (Fig. 2C–F). SS125 showed spherical structures with coarse and disoriented clusters and distinct granules (Fig. 2C, D), indicating a lower degree of carbonization. As HTT increased to 225 °C, more pores were observed along with sponge structure in SS225 (Fig. 2E, F), mainly due to the release of volatile matter such as organic acids, aldehydes, alcohols, and ketones, as well as the dehydration and deformation of carbohydrates, proteins, and lipids in SS (Nawaz and Kumar 2023; Afolabi et al. 2020). For CM, non-porous flat morphology with irregular shapes and rough surfaces with distinct fibrous structures were observed (Fig. 2G, H). However, CM125 showed wavy surfaces with different sized micropores and small fragments due to the degradation of carbohydrate (Fig. 2I, J), while CM225 had smooth surface and edges with distinct spheres and clustered grape-like floc (Fig. 2K, L). Additionally, more cracks were found in CM225 compared to CM125, likely due to the hydrolysis of carbohydrates at higher HTT (Lang et al. 2019; Nawaz and Kumar 2023).

The FTIR spectra showed that SSCs exhibited higher amounts of O- and N-containing functional groups than CMCs (Fig. 3A, B). For SSCs, the band at 3200–3400 cm⁻¹ attributed to –OH stretching vibration indicated the presence of hydroxyl or carboxylic groups, which were clearer in SS225 than SS125 (Fig. 3A, Table S2). These results are consistent with the van-Krevelen diagram (Fig. 3C), which showed that HTC at 225 °C resulted in lower H/C and O/C ratios than 125 °C for both SSCs and CMCs, suggesting the higher degree of decarboxylation and carbonization at higher HTTs (Han et al. 2016). Interestingly, the O/C ratios of SSCs were lower than those of CMCs, even though SS had higher O/C than the CM, which might be resulted from the higher decarboxylation of SS during HTC (Han et al. 2016).

The peak at 2920 assigned to –OH stretching of carboxylic acids, C–H stretching of alkane group and N–H stretching of amine salts, was sharper in SS225 than in SS125. A peak appeared at 2852 in SS225 attributed to –OH stretching of carboxylic acids, N–H and C–H stretching of amine salts, indicated the presence of hydroxyl and amine groups on SSCs. The band intensities at 1600–1700 cm⁻¹ denoted to C=O asymmetric stretching and C=C vibration showed the presence of carboxyl or aldehyde groups in SSCs. The peaks at 1020–1030 cm⁻¹ were attributed to C–O–C vibrating and stretching, which can also be assigned to the –Si–O stretching due to the presence of SiO₂ (Peng et al. 2016). These peaks shifted to 1007 cm⁻¹ in the SS225 probably due to the high deoxygenation and decarboxylation reactions during HTC. Consistently, the aromatic C peaks such as C=O, C=C and C–H were less intense in CM225 than CM125 (Fig. 3B). The bands at 3200–3400 cm⁻¹ assigned to –OH stretching vibration appeared sharper in CM125 than in CM225, probably due to the dehydration reactions. The peaks at 2900–2925 cm⁻¹ represented the aliphatic C–H stretching vibration of methylene groups. For CM225, this peak exhibited a lower intensity compared to CM125, which could be attributed to the depolymerization and cracking of organic compounds during the hydrothermal carbonization process (Nawaz and Kumar 2023). The band intensities at 1600–1700 cm⁻¹ were denoted to C=O asymmetric stretching and C=C stretching in CM125 (Wu et al. 2017). This band shifted to 1591 cm⁻¹ in SS225, which was attributed to C=C stretching of aromatic C and showed the high degree of carbonization in CM225 compared to CM125.

In summary, the elemental and structural characteristics of SSCs and CMCs were found to be largely influenced by the feedstock type and HTT (Fig. 3D). HTC increased C content while decreasing O and H contents in the hydrochars, and CMCs have higher C contents than SSCs. Ash contents in the hydrochars

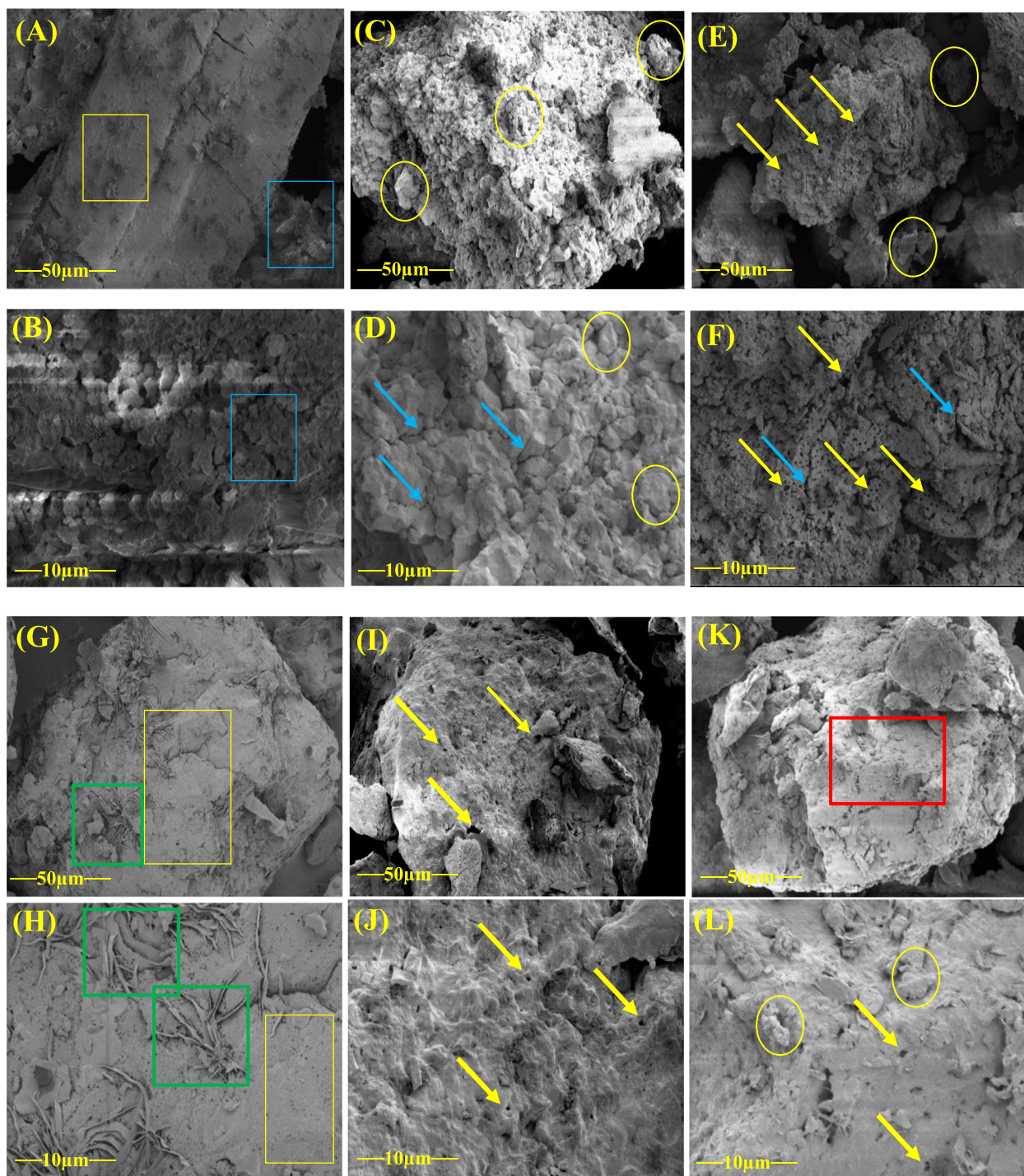


Fig. 2 The representative SEM images of the sewage sludge and chicken manure hydrochars. (A, B) SS; (C, D) SS125; (E, F) SS225; (G, H) CM; (I, J) CM125; (K, L) CM225. SS: sewage sludge; CM: chicken manure; SS125 and SS225: sewage sludge derived hydrochar produced at 125 and 225 °C; CM125 and CM225: chicken manure derived hydrochar produced at 125 and 225°C. Colored boxes show the specific surface morphologies (yellow: non-porous, flat; red: smooth; green: fibrous; blue: dense, amorphous); the yellow arrows indicate the different size pores; and the blue arrows show the cracks; and the circles show the spherical morphology

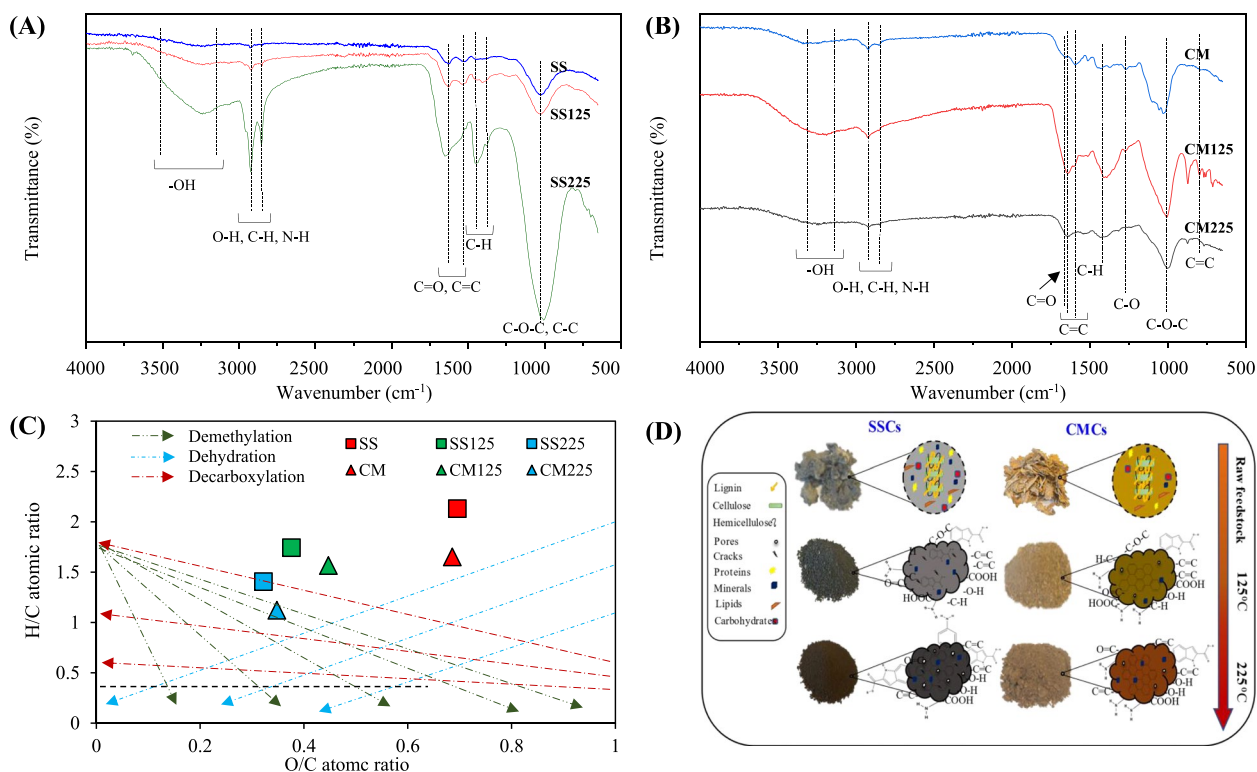


Fig. 3 The FTIR spectra (A, B), van Krevelen diagram of bulk elemental ratios (C), and schematic diagram of the sewage sludge and chicken manure derived hydrochars (D). The increasing HTT results in the alteration of physicochemical properties of the hydrochars (e.g., functional groups, pores, cracks, and elemental composition). SS: sewage sludge; CM: chicken manure; SS125 and SS225: sewage sludge derived hydrochar produced at 125 and 225 °C; CM125 and CM225: chicken manure derived hydrochar produced at 125 and 225 °C

remained relatively stable, while the total contents of P increased. Distinct morphological differences were observed between SSCs and CMCs. SSCs exhibited more porous structures as HTT increased, and showed higher amounts of O- and N-containing functional groups than CMCs. These hydrochars with distinct characteristics may result in different performances in agricultural applications, which is discussed in the following section.

3.2 Enhanced soybean and corn growth by the different hydrochars

For soybean, the application of SSCs had little influence on its total biomass, while the application of CMCs increased its total biomass by 23.2–66.2% relative to the control (Fig. 4A). SS225 treatment showed a slight decrease in soybean SDW, whereas CM125 treatment significantly increased soybean SDW by 41.5% and RDW by 142% relative to the control (Fig. 4B). Moreover, both SS125 and CM125 applications increased soybean chlorophyll content by 21.7% and 20.5% relative to those of the control, respectively (Table S3). These results implied that the type of feedstocks should be taken into consideration when hydrochar is used as a

fertilizer since it can greatly affect the growth and productivity of the plant species (Melo et al. 2018). Thus, the choice of hydrochar should ideally be based on crop type and growth stages.

For corn, both SSCs and CMCs increased its total biomass by 32.8–92.4% and 21.8–69.7%, respectively, compared to the control (Fig. 4C). The hydrochars produced at the lower HTT (SS125 and CM125) had more pronounced effects on both SDW and RDW of corn than those produced at the higher HTT (SS225 and CM225). In particular, the application of SS125 significantly increased SDW by 86.2% and RDW of corn by 140% compared to the control, much higher than those of CM125 (63.1% and 120%; Fig. 4D). Additionally, compared to the control treatment, the applications of SS125 and CM125 increased the chlorophyll content of corn seedlings by 45.3% and 29.6% and the number of corn leaves by 17.4% and 30.6%, respectively (Table S3). Interestingly, little difference in soybean and corn growth parameters in the triple super phosphate (TSP) treatment compared to the hydrochars was observed (Fig. 4), implying that SSCs and CMCs were more effective in enhancing the growth and productivity of corn.

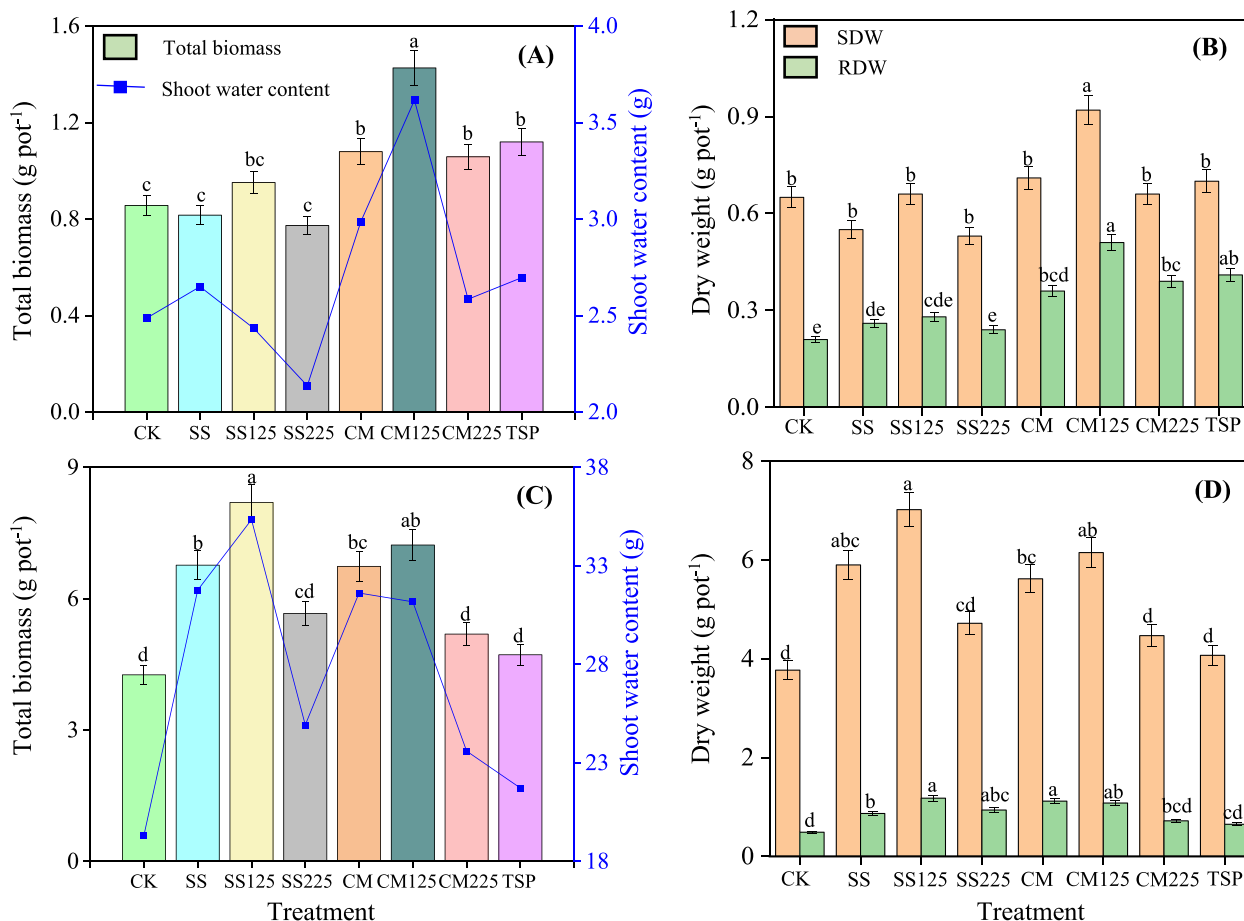


Fig. 4 Effect of the hydrochar application on the total dry biomass (TPB), shoot water content (SWC), shoot (SDW) and root dry biomass (RDW) of soybean (A, B) and corn (C, D). CK: control soil without any amendments; SS: soil added with sewage sludge; CM: soil added with chicken manure; SS125 and SS225: soil added with sewage sludge derived hydrochar produced at 125 and 225 °C; CM125 and CM225: soil added with chicken manure derived hydrochar produced at 125 and 225°C; TSP: soil added with triple super phosphate, a conventional P fertilizer. Different lowercase letters indicate significant differences between different soil treatments by Duncan’s New Multiple Range Test at $p < 0.05$

Overall, these findings support our hypothesis that these hydrochars can be effectively used as soil amendments to enhance crop growth.

The observed differences in growth response can be attributed to the varying nutrient availability in the hydrochars, with the ones produced at lower temperatures containing more readily available nutrients than those produced at higher temperatures (Fig. 1). The improved plant growth can be ascribed to several factors, including the high nutrient content of hydrochars (Khosravi et al. 2021; Melo et al. 2018), the improved soil physicochemical properties and the increased retention of nutrients in the soils (Shi et al. 2019; Fei et al. 2019b). The specific role of P in contributing to the enhanced growth of soybean and corn, including its uptake dynamics, and the potential impact of the hydrochar amendments on P availability and utilization, is discussed in detail in the following section.

3.3 Increased P uptake by soybean and corn grown in the hydrochar-amended soils

In order to investigate P fertilization potential of the hydrochars in the soils grown with soybean and corn, shoot P uptake (SPU) and P use efficiency (PUE) were evaluated. The application of SSCs and CMCs showed significant effects on SPU and PUE of the two crops. Specifically, compared to their respective controls, SS125 and CM125 increased SPU by 45.3% and 52.2% for soybean, and by 65.7% and 104.4% for corn, respectively (Fig. 5A, B). These results implied that the hydrochars enhanced P availability and root accessibility, resulting in the increased P uptake (de Jager and Giani 2021). Intriguingly, for soybean, SS225 reduced SPU by 17.8% compared to the control and 43.4% compared to SS125 (Fig. 5A, Table S4), suggesting the greater efficacy of the hydrochars produced at lower temperatures for P uptake by crops. The decreased SPU by the

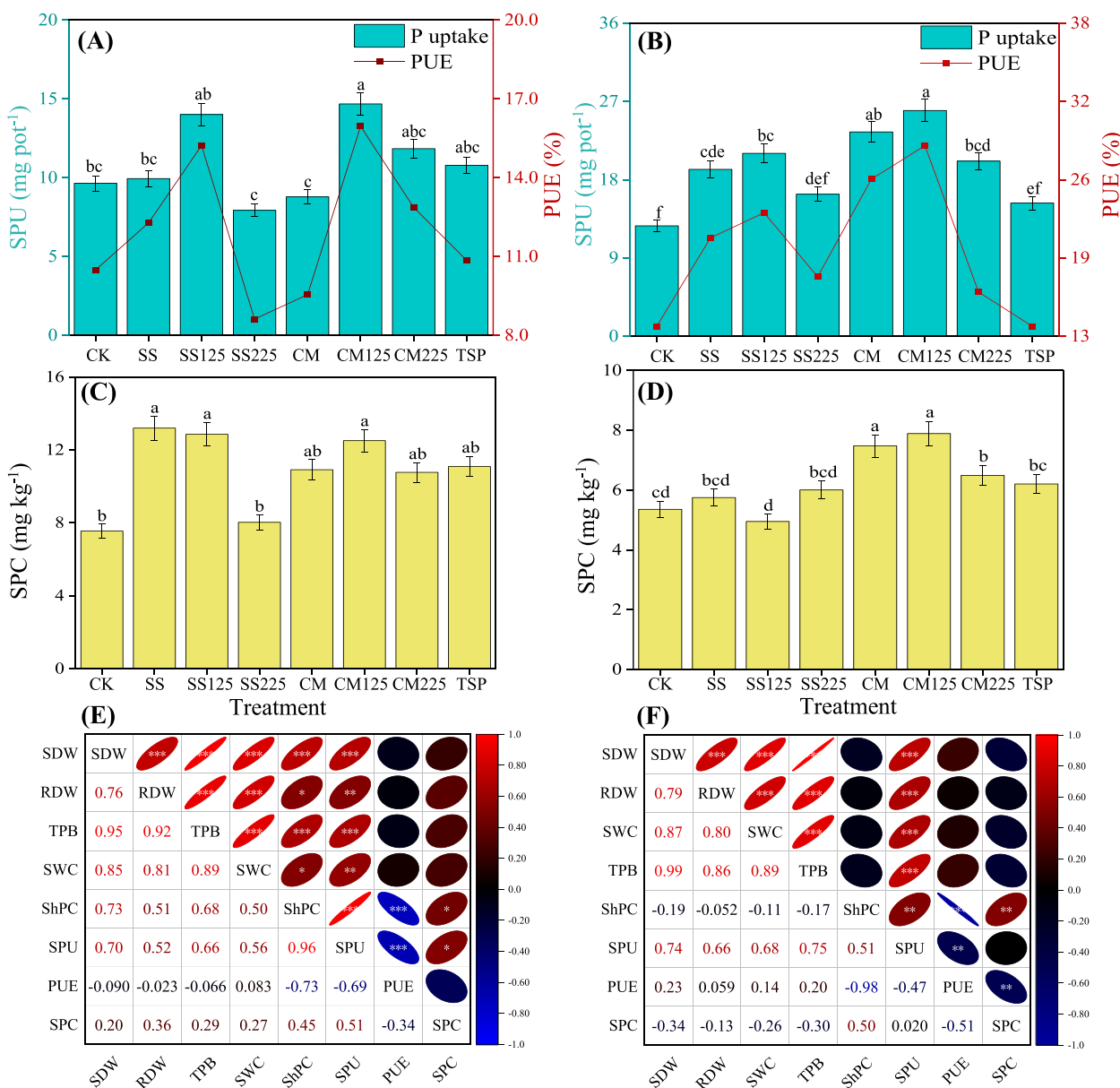


Fig. 5 Effect of hydrochar application on shoot P uptake (SPU) and P use efficiency (PUE), and soil P concentration (SPC) of soybean (A, C) and corn (B, D). Pearson correlation matrix of the growth parameters and P content of soybean (E) and corn (F) and the soils. Colors from blue to red represent changes in the Pearson correlation coefficient from -1 to 1, while the symbols *, **, and *** represent significant correlations at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$. CK: control soil without amendments; SS: soil added with sewage sludge; CM: soil added with chicken manure; SS125 and SS225: soil added with sewage sludge derived hydrochar produced at 125 and 225 °C; CM125 and CM225: soil added with chicken manure derived hydrochar produced at 125 and 225 °C; TSP: soil added with triple super phosphate, a conventional P fertilizer. ShPC: shoot P concentration; SDW: shoot dry weight; PUE: P use efficiency, the ratio of produced biomass to unit of P uptake; RDW: root dry weight; TPB: total dry biomass; SWC: shoot water content; SPU: shoot P uptake; SPC: soil P concentration. Different lowercase letters indicate significant differences between different soil treatments which were analyzed by Duncan's New Multiple Range Test ($p < 0.05$)

application of SS225 may be attributed to the higher stable P in SS225 (Table S1), the enhanced P sorption by precipitation due to higher Ca and Mg content (Fig. 1 C and D; Takaya et al. 2016), and the richer porous structure of SS225 leading to P retention (Nawaz and

Kumar 2023; Afolabi et al. 2020). The reduced SPU can influence both crop yield and nutritional quality. Notably, the high amount of P input in soils generally raises ecological concerns such as eutrophication (Liu et al. 2023a). Additionally, growers may add supplementary

P fertilizers to increase plant P uptake which results in economic ramifications.

Moreover, CM125 increased SPU by 4.7% in soybean and 23.4% in corn compared to SS125, indicating the higher P availability in the soils amended with CMCs than SSCs. The increased P uptake in the present study is consistent with previous research reported by McIntosh et al. (2022), who found a 5-fold increase in wheat P uptake after applying sewage sludge hydrochar (McIntosh et al. 2022). Additionally, TSP exhibited minimal impact on SPU compared to the control and the hydrochar treatments grown with both soybean and corn (Fig. 5A), suggesting that the hydrochars can be used as an effective alternative to chemical P fertilizers.

P use efficiency (PUE), referring to the amount of P absorbed by the plant per unit of the applied P fertilizer (Chen and Graedel 2016; Zheng et al. 2018), showed a similar trend to SPU (Fig. 5A, B). Compared to their respective controls, SS125 and CM125 increased PUE by 45.2% and 52.1% for soybean, and by 65.6% and 104.3% for corn, respectively (Fig. 5A, B). The increased PUE after the application of hydrochar indicated that the plant was utilizing the available P more efficiently per unit of hydrochar applied (Wang et al. 2017). These results further proved our hypothesis that hydrochars can increase P uptake and are potential P fertilizers for plant growth demands. Importantly, feedstock type strongly influences P availability in hydrochars (Huang et al. 2018), which explains the higher P uptake and PUE in CM125 than SS125 (Fig. 5A, B). As an explanation, over 50% of P in CM125 was present in the water-soluble form, which can be rapidly released into the soils and absorbed by plants (Table S1), leading to the increased SPU and PUE for soybean and corn with CM125 treatments. In addition, HTT plays a key role in determining P availability of the hydrochars (Fig. 1). Particularly, higher HTTs increase P stabilization in hydrochars and decrease moderately labile P (Wang et al. 2021a), thus resulting in the higher SPU and PUE in the treatments with the hydrochars produced at lower HTTs (SS125 and CM125) than the higher HTT (SS225 and SS225). High water soluble P might be a desirable goal in short term plant production (Mahfuz et al. 2014), which narrates the application of commercial P fertilizers like TSP, but it can increase the risk of soil P leaching (Melo et al. 2019).

3.4 Improved P availability in the hydrochar-amended soil

In order to confirm the role of hydrochars in increasing P availability in the soil, exchangeable P content in the soils was further examined after the plant harvest (Fig. 5C, D). In both soybean and corn, the SPC increased with SSCs, and CMCs treatments compared to the controls. Specifically, for soybean, SPC increased

by 6.3–70.3% in SSCs treatment and 42.6–65.7% in CMCs treatment, and for corn, by 8.1–21.3% in SSCs treatment and 31.1–59.3% in CMCs treatment (Fig. 5C, D). These results validated our hypothesis that hydrochars improved soil P availability. Furthermore, SPC in the higher temperature hydrochar (SS225 and CM225) treatments was less than the lower temperature hydrochars (SS125 and CM125) by 37.5% and 13.9% in soybean and 61.9 and 47.5% in corn (Fig. 5C, D, Table S5). These results highlighted the critical role of HTT in determining soil P availability amended with hydrochars, demonstrating that lower HTT is more effective in increasing SPC (Huang et al. 2018). A significant positive correlation between SPC and SPU values supported the notion that hydrochars have considerable potential as P fertilizer (Fig. 5E, F, S2). Additionally, there was no significant difference in the SPC between the TSP and hydrochar treatments, further suggesting that hydrochars can be used as an alternative to chemical P fertilizers.

It is important to consider the types of feedstocks, HTC conditions, and plant species in P fertilization by hydrochar. HTC is operated in aqueous environments involving chemical reactions such as hydrolysis, decarboxylation, and polymerization, may result in interactions between P and metallic oxide or metals like Ca, Fe, and Al (Huang and Tang 2016). This in turn can lead to the formation of more stable metal-P complexes such as Al and Fe-associated phosphate in hydrochars (Table S1). These metal-P complexes might be inaccessible to plants or released slowly into the soil (Shi et al. 2019; Huang and Tang 2016), which may cause the lower SPC in the soybean grown soil treated with SS225 compared to SS125 (Fig. 5C). The lower SPC in the SS225 treated soil was also due to a higher concentration of stable P (HCl extractable P) in SS225 (Huang et al. 2018). In addition, the P fractions in CMCs are primarily in the form of water-soluble P (Huang et al. 2018), leading to the high SPC for both soybean and corn. However, it is important to note that SS125 significantly increased SPC compared to the control in soybean (Fig. 5C), while it showed little effect on SPC for corn compared to the control (Fig. 5D). This phenomenon may result from the different root systems between soybean and corn. Soybean, legume, generally forms symbiotic associations with rhizobium species involved in N fixation and contributes to the increased P uptake (Thioub et al. 2019). These bacteria can also solubilize phosphate minerals (e.g., apatite) through the production of organic acids such as citric, oxalic, and malic acids, which can be readily available for plant uptake (Egamberdieva et al. 2020). Given that a significant proportion of P in SS is bound to aluminum (AlPO_4) and is either inaccessible to plants or slowly released into the

soil (Huang and Tang 2016), the presence of rhizobium species in soybean roots may substantially increase SPC.

3.5 Increased P retention in the hydrochar-amended soil

In order to better understand the performance of hydrochar as a slow-release P fertilizer, WSP was tested in the soil columns at four depths (0–5, 5–10, 10–15, and 15–20 cm) and two time points (one and six months). The application of SSCs and CMCs increased WSP concentration by 3.8–13.0% and 38.2–56.12%, respectively, to the control (Table S8), demonstrating the high contents of soluble P in the hydrochars (Huang and Tang 2016). In addition to the fact that the hydrochars exhibited lower content of WSP than their corresponding feedstocks in the soils, SS225 application resulted in an 8.1% decrease in WSP content compared to SS125. Similarly, CM225 treatment resulted in a 11.4% decrease in WSP content compared to CM125, implying that high HTT decreased the WSP in the hydrochars due to the stabilization of P with other elements such as Ca, Mg, Fe and Al (Huang et al. 2018). In addition, CMCs generally showed higher content of WSP than SSCs in the soils due to the presence of inherent water-soluble P which increases the direct input of WSP to the soil (Huang et al. 2018). Predictably, TSP increased WSP levels by 34.9% compared to the control,

but little difference was observed when compared with the CMCs (Table S8). Regardless of the type of amendments (i.e., hydrochar, SS, CM, and TSP) applied to the soil, the concentration of WSP increased over time, from 4.96 mg kg⁻¹ in 1 month to 5.45 mg kg⁻¹ after 6 months (Table S9). In addition, WSP content decreased by 45.4%, 61.8% and 61.9% at the depth of 5–10 cm, 10–15 cm, and 15–20 cm, compared to the surface soil (0–5 cm), respectively (Table S9). The differences in WSP concentration across the different soil depths can be explained by the interactions between the hydrochars and soils since hydrochars can influence P dynamics in the soil profiles (Huang and Tang 2016). After 1 month of incubation, CM125 and SS125 increased the WSP concentration of the surface soil (0–5 cm) by 292% and 143% compared to the control (Fig. 6). This suggested that these hydrochars initially enhanced P availability by the release of inherent P in the hydrochars. Contrastingly, SS225 decreased the WSP concentration of the surface soil by 17.3% compared to the control, indicating the decreased P solubility and availability in hydrochar. This reduction could be due to the immobilization of P by different cations such as Ca and Mg present in SS225 (Fig. 1, Table S1). This observation aligned with previous studies demonstrating the role of biochars in P immobilization via surface adsorption

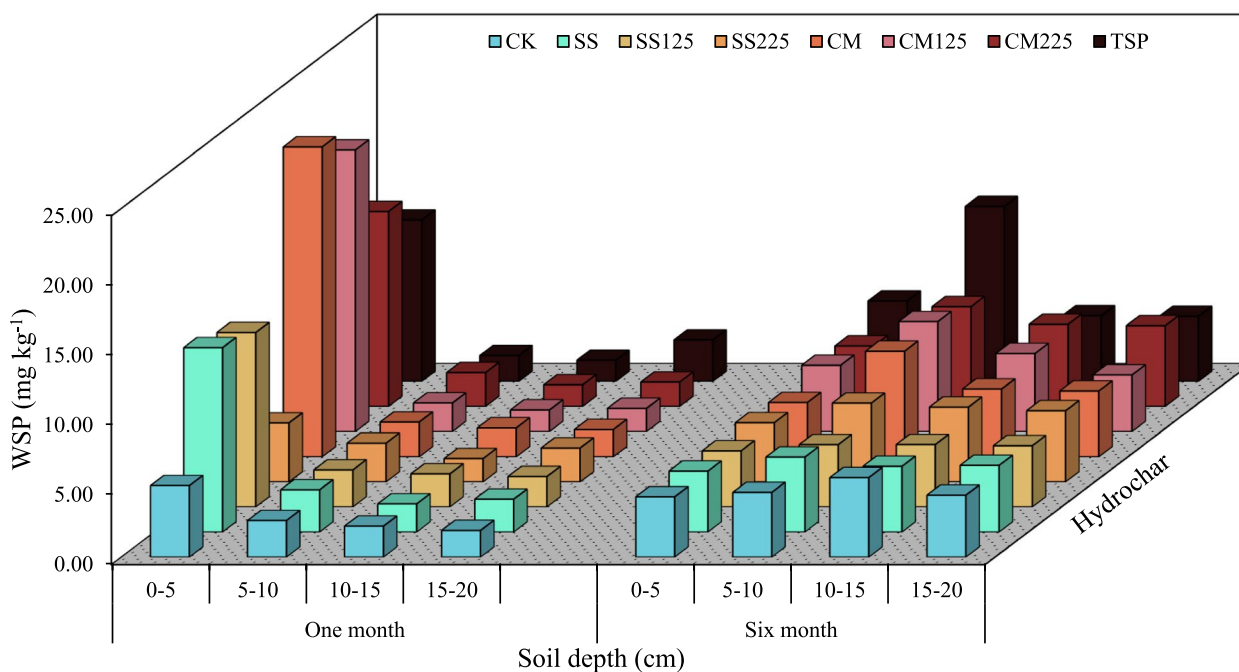


Fig. 6 Effect of hydrochars, and soil depth on the concentrations of water soluble P (WSP) in the soil columns after the incubation for one month (a) and (b) six months. CK: control soil without amendments; SS: soil added with sewage sludge; CM: soil added with chicken manure; SS125 and SS225: soil added with sewage sludge derived hydrochar produced at 125 and 225 °C; CM125 and CM225: soil added with chicken manure derived hydrochar produced at 125 and 225 °C; TSP: soil added with triple super phosphate. Significant results of the Duncan’s multiple-comparison test ($p < 0.05$) for this figure are reported in Table S8

(McIntosh et al. 2022; Huang et al. 2018). The concentrations of WSP in the soils at other depths without hydrochar application were not significantly different in all the treatments, further proving that P in the surface soil amended with the hydrochar is not readily leached out to the deeper soils in the short period of 1 month (Fig. 6).

The WSP concentrations increased in all the soils at all the different depths after 6 months compared with the control (Fig. 6). In particular, the soil at 5–10 cm depth in the CM125 treatment showed a 69.8% increase in WSP compared to that in the control. However, the WSP concentration at 0–5 cm depth in the CM125 treatment decreased by 76.4% after 6 months compared to the first month of incubation. Similar results were also observed for those in the CM225 treatments. This stabilization of WSP levels in the soils treated with the hydrochars can be attributed to the functional groups, elements, high surface area and porosity of the hydrochars, which can lead to P adsorption via precipitation, electrostatic attraction, and ion exchange

(Ghanim et al. 2018; Liu et al. 2023a). Furthermore, the high contents of Ca and Mg in the hydrochars can result in the fixation of P in the soil, decreasing its water solubility and mobility (Huang et al. 2018). Additionally, the soil at 5–10 cm depth in the TSP treatment showed a significant increase of 576% in WSP compared to the 0–5 cm soil depth, and 169% compared to the same depth in the control (Fig. 6). These results indicated a higher content of WSP in TSP than in hydrochars, which did not decrease over time. The high WSP in TSP makes it easier for P to move through the soil profile and increase the P leaching (Cui et al. 2021; Frazão et al. 2019; Aragón-Briceño et al. 2021). These results suggested that the WSP concentration increased upon the application of hydrochars, which supports our hypothesis that hydrochars can be used to directly release P in the soil for plant growth and indirectly increase soil P retention and decrease soil P leaching (Fig. 7).

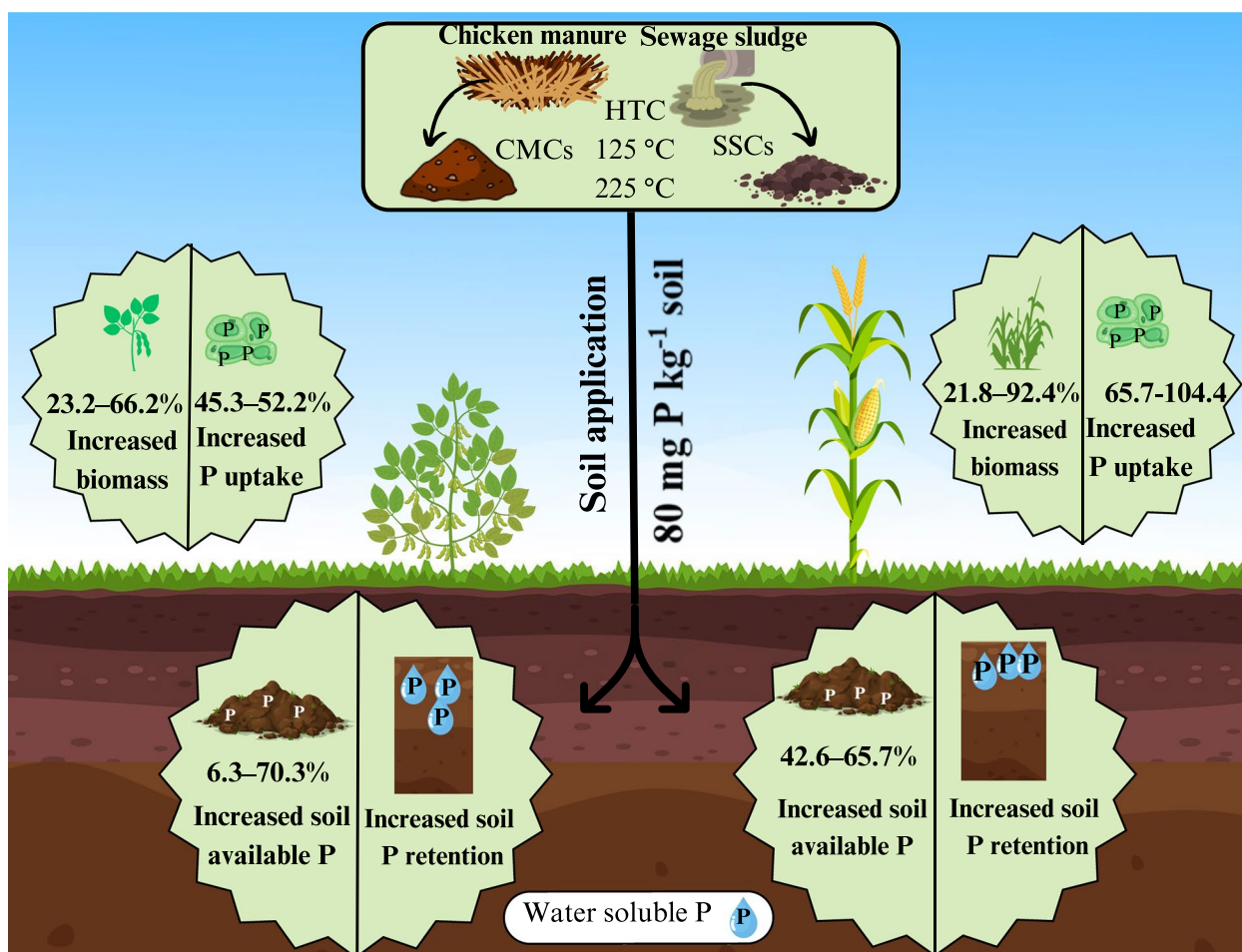


Fig. 7 Schematic diagram showing the performance of chicken manure-derived hydrochars (CMCs) and sewage sludge derived-hydrochars (SSCs) in enhancing the growth of soybean and corn and P availability in the soil. The hydrochars contained high contents of P and functional groups (e.g., O and N containing functional groups), thus increasing the total biomass and P availability (concentration, uptake, and retention) in the soil

4 Conclusion and environmental implications

This study comparatively investigated the physico-chemical properties of two batch of hydrochars produced from SS and CM (SSCs and CMCs) at different HTTs and their P fertilization potential in soybean and corn growth in an agricultural soil. SSCs with higher porosity and rougher surface exhibited lower C content, higher ash and P content compared to CMCs. Hydrochars produced at higher HTTs (SS225 and CM225) showed higher C and ash contents, and lower H and O contents than those produced at lower HTT (SS125 and CM125). All the hydrochars featured C-O, C-H, and C=C functional groups, with SSCs showing a high content of N-containing functional groups.

Both soybean and corn growth significantly improved with the use of hydrochars, especially those from CM, primarily due to their nutrient provision, particularly P, and improved uptake. The increase in soil and shoot P uptake in hydrochar treatments underscores their potential as viable alternatives to chemical P fertilizers. Application of hydrochars augmented WSP concentration in soils, helping to prevent soil P leaching and providing a possible slow-release P fertilizer. The agricultural industry, facing issues like soil degradation, can apply hydrochars as a potential solution for sustainable soil management through decreasing the use of chemical fertilizers. Additionally, by reducing P runoff, hydrochar may provide an answer to the water pollution from excess nutrients leaching. Furthermore, using hydrochars as an alternative P fertilizer might lead to cost-effective farming practices. Future research should assess fertilization capacities of hydrochars for other key macronutrients, such as N and K, and micronutrients, as well as their effectiveness in varying soils and crop types. In addition, the soil health following hydrochar application should also be evaluated based on the presentative physical, chemical, and biological attributes targeted at soil ecosystem multifunctionality.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44246-023-00086-w>.

Additional file 1.

Authors' contributions

All authors contributed to the study conception and design. Hao Zheng and Baoshan Xing performed the supervision, conceptualization and funding acquisition. Material preparation, data collection and analysis were performed by Anahita Khosravi, Yanfei Yuan and Qiang Liu. The first draft of the manuscript was written by Anahita Khosravi, Yanfei Yuan, Qiang Liu, Masoud Hashemi, and Yuanzhi Tang commented on previous versions of the manuscript. The submitted version of the manuscript was finalized by Hao Zheng and Baoshan Xing. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

Boshan Xing is an editor of *Carbon Research*, but was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no competing interests.

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