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Enhanced soil aggregation and reduced colloidal phosphorus loss by straw biochars in tea and medicinal herb cropping systems

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ABSTRACT

Phosphorus (P) loss in agricultural runoff significantly contributes to water eutrophication, yet effective mitigation strategies remain limited. This study aimed to assess the impact of biochar amendments on P loss and soil properties in two cropping systems in Zhejiang Province, China: tea and medicinal herb cropping systems. Field experiments compared four fertilization treatments: no fertilization, conventional fertilization (CF), and CF with the partial substitution of chemical fertilizer by 1.5 t ha^{-1} rice straw biochar (CFRB) or corn straw biochar (CFCB). Over the monitoring period, the study assessed the impact of straw biochars on P loss in different forms and soil properties (soil organic carbon, pH, and soil aggregation). Results showed colloidal P accounted for 41.4 % and 29.7 % of total P losses in the tea and medicinal herb cropping systems, respectively. Biochar amendments (CFRB and CFCB) significantly reduced total P and colloidal P losses across both cropping systems, decreasing colloidal P losses by up to 30.4 % compared with CF. This was primarily due to biochar amendments enhancing soil organic carbon and elevating soil pH, which improved soil aggregation by increasing the proportion of small and micro-aggregates by 3.7 %–9.0 %, effectively limiting the transport of P-bound colloids. These findings highlight the role of biochar as an effective, sustainable solution for mitigating P loss in tea and medicinal herb cropping systems.

1. Introduction

Phosphorus (P) loss from agricultural soils poses a significant environmental challenge, contributing to the eutrophication of freshwater systems (Siebers et al., 2023). While considerable research has explored P runoff loss in paddy systems (Wang et al., 2019a), studies investigating tea plantations and dryland cropping systems remain limited. Tea plantations constitute an important part of global agricultural land use, with China accounting for 64.65 % of the world's harvested tea area in 2021 (FAO, 2022). Tea plantations, typically managed as perennial systems with dense canopy cover and deep root architecture on sloped terrain using contour planting, often experience significant nutrient runoff loss due to intensive fertilizer application and periodic heavy rainfall (Ni et al., 2019). Similarly, dryland cropping systems, including medicinal herb cultivation, are projected to expand by 2100 and could account for 56 % of the global land surface due to climate change (Huang et al., 2017). Drylands experience irregular rainfall patterns and frequent wet-dry cycles, which, combined with intensive fertilization and frequent tillage, can disrupt soil structure, amplify P mobility, and accelerate nutrient transport (Wang et al., 2022). However, limited attention has been given to how these systems differ in P cycling behavior, fertilization intensity, and soil management, all of which can influence runoff P forms. Addressing these differences is essential for designing context-specific nutrient management strategies.

Traditionally, research on P migration has primarily focused on dissolved total P (DTP) and particulate P (PP), with a boundary of 450 nm used to distinguish between the two (Hens and Merckx, 2002). This framework assumes that P either remains in stable solid phases or migrates with water. However, it neglects the importance of colloidal P (CP) in the dynamics and transport of soil P (Wang et al., 2024). CP,

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defined as fine particles ranging from 1 to 1000 nm in size, exhibits unique properties that significantly influence P mobility in soils (Li et al., 2019). Due to its high specific surface area and reactive functional groups, CP can adsorb substantial amounts of P, serving as a mobile reservoir for P loss from soils (Chen and Arai, 2020). Unlike PP, which eventually settles due to gravity, CP is maintained in suspension by Brownian motion, enhancing its transport potential and posing significant risks for long-distance P loss (Warrinnier et al., 2019). CP concentrations in agricultural soil runoff, leachate, and lake water bodies can exceed 50 % of the total P (TP) concentration (Missong et al., 2018).

The release and transport of CP are influenced by multiple factors, including soil physicochemical properties and environmental conditions (Li et al., 2021b). Key drivers include soil mineral composition and changes in soil chemical conditions such as organic matter content, pH, and moisture. For example, studies have shown that pH plays a pivotal role in regulating CP behavior. Under acidic conditions, the dissolution of inorganic binding agents (e.g., Al and Fe oxides) can enhance CP release, whereas under alkaline conditions, the removal of organic coatings from colloidal surfaces also promotes CP mobilization (Liang et al., 2010). Additionally, soil organic carbon (SOC) can directly impact CP formation by interacting with Fe- and Al-bound colloids, influencing their aggregation or dispersion (Sowers et al., 2019). However, studies on CP in tea plantation and dryland systems remain limited, even though these systems exhibit distinct soil properties, management practices, and runoff dynamics that may significantly influence CP behavior. This knowledge gap constrains our mechanistic understanding of CP transport across diverse land-use types.

Fertilization practices play a significant role in regulating CP loss (Li et al., 2021a), as they directly influence soil nutrient availability, structure, and chemical properties. Biochar, a widely used soil amendment, presents a more complex role in CP dynamics. Its large specific surface area and abundant functional groups can immobilize soluble P by enhancing adsorption and aggregation (Laird et al., 2010). However, biochar's high porosity and inherent soluble P content may facilitate preferential flow and increase P leaching under specific hydrological conditions (Madiba et al., 2016). These contrasting effects are further modulated by biochar's ability to modify key soil properties. Biochar can increase soil pH, reduce the number of exchangeable ions, and thus reduce P adsorption (Ch'Ng et al., 2014). Additionally, biochar contributes to SOC enhancement, which affects CP behavior through two opposing mechanisms. On the one hand, increased SOC can stabilize soil aggregates, reducing colloidal transport; on the other hand, SOC may increase the P adsorption saturation of colloidal particles, and promote the loss of CP through surface runoff or underground leaching (Li et al., 2019). These multifaceted interactions underscore the need for a nuanced understanding of how biochar influences CP loss, particularly under different soil textures, fertilization regimes, and hydrological conditions.

To address these gaps, this study conducted annual monitoring of straw biochar amendments on P loss and soil properties in two distinct cropping systems: a tea and a medicinal herb cropping system in Zhejiang Province, China. In this study, straw-derived biochars (from rice and corn) were selected for field application. These materials are among the most common agricultural residues in southeastern China, offering a sustainable and locally abundant resource for biochar production. Moreover, their use aligns with circular agriculture principles by converting waste biomass into high-value soil amendments. Specifically, the study aimed to: 1) quantify and compare P (TP, PP, DTP, and CP) loss concentrations and loads in runoff, with a focus on CP contributions under different cropping systems; 2) evaluate the effect of straw biochar amendments on P losses and soil properties, including soil aggregation, SOC, and pH; 3) identify key factors influencing P loss dynamics. Based on the properties of straw biochar and its interactions with soil and P dynamics, we propose the following hypotheses: 1) Straw biochar amendments will reduce CP and TP loss in runoff by enhancing soil aggregation and modifying soil chemical properties; 2) The effectiveness of biochar in reducing P loss will vary across cropping systems due to differences in soil texture, baseline fertility, and runoff characteristics. This research provided novel insights into the mechanisms of CP loss and demonstrates the potential of straw biochar as a viable strategy for P loss mitigation in cropping systems.

2. Method and materials

2.1. Experimental sites and design

From October 2020 to May 2022, field experiments were conducted at two observation sites in Zhejiang Province, China, representing different cropping systems: a tea cropping site in Kaihua County, Quzhou City (KH, 118°16′26″E, 29°5′59″N) and a medicinal herb cropping site in Pan'an County, Jinhua City (PA, 120°22′17.9″E, 28°54′4.5″N). Both sites experience a subtropical monsoon climate, with average annual temperatures of 16.6°C at KH and 15.4°C at PA. According to the USDA soil texture classification using the hydrometer method (García-Gaines and Frankenstein, 2015), the soils at KH and PA were classified as clay loam and sandy loam, respectively. Detailed soil physical and chemical properties are provided in Table 1.

Four treatments were applied at each site, with three replications per treatment, resulting in a total of 12 monitoring cells per cropping system. A consistent P application rate was maintained across all fertilizer treatments within the same system. The treatments were as follows: 1) no fertilization (control; CK), 2) conventional fertilization (CF), 3) the application of 1.5 t ha^{-1} of rice straw biochar to partially replace compound fertilizers in CF (CFRB), and 4) the application of 1.5 t ha^{-1} of corn straw biochar to partially replace compound fertilizers in CF (CFCB). For all fertilization treatments, the P input rate was approximately 45 kg P ha^{-1} in the tea plantation and 150 kg P ha^{-1} in the medicinal herb cropping system. In the CFRB and CFCB treatments, biochar replaced 9.60 % and 6.87 % of the compound fertilizer, respectively, in the tea cropping system, and 20.56 % and 14.46 % in the medicinal herb cropping system. The detailed fertilization regimes are provided in Tables S1–S2. The properties analysis of biochar is shown in Table S3. To enable monitoring of surface runoff, collection pools were established between the two parallel cells at each site. All treatments adhered to conventional irrigation methods and agricultural practices commonly used by local farmers.

2.2. Runoff sampling and analysis

Runoff samples were gathered using the method described by Li et al. (2021a). A total of twelve runoff collection pools were set up to gather water samples. Samples were collected when the cumulative water depth exceeded half the height of the pool. Following each sampling event, the pools were emptied to prepare for the next round of collection. Samples were then stored at 4 °C.

Table 1
Basic physical and chemical properties of soils at the observation sites.

	KH	PA
pH	5.89 ± 0.13	7.07 ± 0.06
Sand (%)	28.12 ± 1.20	60.46 ± 3.06
Silt (%)	35.08 ± 2.17	29.43 ± 1.70
Clay (%)	36.80 ± 1.26	10.11 ± 1.34
Total C (mg kg^{-1})	15620 ± 220	25100 ± 230
Total P (mg kg^{-1})	810 ± 40	1010 ± 30
Total N (mg kg^{-1})	1840 ± 250	2120 ± 150
Total K (mg kg^{-1})	577.06 ± 58.90	603.55 ± 43.20
Available N (mg kg^{-1})	9.62 ± 0.76	15.32 ± 1.58
Available P (mg kg^{-1})	87.32 ± 1.23	76.42 ± 2.34
Available K (mg kg^{-1})	151.58 ± 27.31	166.29 ± 10.02
Colloidal P (mg kg^{-1})	6.77 ± 0.27	4.12 ± 0.16
Maximum water holding capacity (%)	42.04 ± 1.73	35.17 ± 1.88

Note: KH is the Kaihua observation site; PA is the Panan observation site.

The monitoring indicators in runoff include TP, DTP, PP, and CP. Each water sample was analyzed in triplicate. TP concentration was measured by molybdenum blue colorimetry and UV–visible spectrophotometry (Murphy and Riley, 1962). DTP was determined from a portion of the sample filtered through a 0.45 μm membrane, while PP was calculated as the difference between TP and DTP. CP was measured from a separate portion of the water sample using a multi-step filtration and centrifugation process. First, large particles were removed by centrifuging the sample at 3000 × g for 10 min. The supernatant was then filtered through 1000 nm microporous membranes (Sartorius, Germany), replacing the membranes every 20 mL to prevent pore clogging. The filtrate, containing both CP and truly dissolved P ($\leq$ 1 nm), was designated as Sample I. A 15 mL portion of Sample I was further filtered using ultrafiltration tubes (Millipore, USA) with a 3 kDa pore size by centrifugation at 4000 × g for 40 min. The resulting filtrate, designated as Sample II, contained only TDP, with colloidal components removed. CP was calculated as the difference between the P content in Sample I and Sample II (Wang et al., 2024).

The runoff volume (V_R) was calculated based on the water depth and pool area, using the following formula:

$$V_R = h \times A$$

where V_R is the runoff volume (m^3), h is the measured water depth (m), and A is the surface area of the runoff collection pool (m^2).

The runoff coefficient was calculated as the ratio of V_R to rainfall. P loss load was determined by multiplying P concentration by V_R. P loss coefficient was computed as the ratio of P loss load to P input.

2.3. Soil sampling and analysis

Soil samples were collected at each runoff event from a depth of 0–20 cm in each treatment plot. Five soil cores were randomly collected per plot and combined into a composite sample. After air-drying, the samples were divided into two portions: one portion was ground and passed through a 0.154 mm sieve for the determination of basic physical and chemical properties, while the other portion was used for soil CP analysis. Soil pH was measured using a glass electrode pH meter (PHS-3C; Shanghai) at a water-to-soil ratio of 5:1. SOC was determined colorimetrically following digestion with K_2CrO_7-H_2SO_4 (Sato et al., 2014). TP was measured using molybdenum blue colorimetry after digestion with H_2SO_4-$HClO_4$. Available P (AP) was extracted using Mehlich-III extractant for acidic soils and with 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) for neutral soils, followed by analysis using the molybdenum blue method (Olsen and Sommers, 1982). The maximum water holding capacity (WHC) was determined using the cutting ring method (Bao, 2000), while the particle size distribution was analyzed hydraulically using the hydrometer method, and classified based on USDA soil texture classification standard (García-Gaines and Frankenstein, 2015). Total carbon and nitrogen were measured with an elemental analyzer (Vario MAX CNS; Elementar, Germany). Soil CP was determined by shaking a soil-water solution (1:8 ratio) at 150 rpm for 16 h, centrifuging at 3000 × g for 10 min, and filtering the supernatant through a 1 μm membrane (Sample I). The filtrate was further processed using a 3 kDa ultrafiltration filter, centrifuging at 3000 × g for 40 min, and collecting the filtrate (Sample II). CP was calculated as the difference in P content between Sample I and Sample II (Wang et al., 2021).

Changes in soil aggregate distribution before and after the monitoring period were assessed using a modified wet-sieving method (Wan et al., 2020). A 100 g unground soil sample was placed on a stacked set of sieves (pore sizes: 2 mm, 0.26 mm, and 0.053 mm) and soaked in deionized water at room temperature for 20 min. The samples were oscillated using an aggregate analyzer (TTF-100) for 10 min at an amplitude of 30 mm and 300 oscillations. Aggregates were separated into large aggregates (>2 mm), small aggregates (0.26–2 mm), microaggregates (0.053–0.26 mm), and silt + clay fractions (<0.053 mm). Separated aggregates were oven-dried at 65 °C for 48 h, weighed, and stored in sealed bags.

2.4. Statistical analysis

Significant differences among the fertilization treatments were assessed using a one-way analysis of variance (ANOVA) performed with SPSS Statistics for Windows (version 22.0; IBM Corp., Armonk, NY, USA). The least significant difference (LSD) test was applied at a significance level of $p = 0.05$ to identify differences between treatment means. Data was visualized using OriginPro 2024 (OriginLab Corp., United States). Pearson's correlation analysis was conducted to evaluate the relationships between variables.

3. Results

3.1. Rainfall and runoff volume

Fertilization treatments showed minimal influence on the V_R at both locations. The variations of precipitation and runoff volume under the two cropping systems are presented in Fig. S1Fig. S1. During the one-year monitoring period, the tea cropping site experienced a cumulative rainfall of 2246.5 mm, leading to 13 runoff events. The average V_R for each treatment was as follows: CK (2846.4 m^3 ha^{-1}), CF (2397.6 m^3 ha^{-1}), CFRB (2192.5 m^3 ha^{-1}), and CFCB (2191.6 m^3 ha^{-1}). The runoff coefficients ranged from 5.4 % to 9.8 %, with an average of 8.5 %. At the medicinal herb cropping site, the cumulative rainfall amounted to 1786.7 mm, resulting 9 runoff events. The average V_R for each treatment was CK (3666.4 m^3 ha^{-1}), CF (3699.9 m^3 ha^{-1}), CFRB (3679.8 m^3 ha^{-1}), and CFCB (3476.5 m^3 ha^{-1}). The runoff coefficients ranged from 19.5 % to 20.7 %, with an average of 20.3 %.

3.2. Changes of different phosphorus fractions in runoff

TP concentration in runoff was closely linked to the timing of fertilization (Fig. 1), with peak values observed shortly after fertilization. The first week after fertilization represented a high-risk period for P loss. At the tea cropping site, TP concentrations initially peaked in July, then gradually declined over the months, reaching another peak in February of the following year. In the medicinal herb cropping system, TP concentrations peaked at the end of May before stabilizing. Runoff TP concentrations ranged from 0.29 to 1.19 mg L^{-1} in the tea plantation and from 0.25 to 2.24 mg L^{-1} in the medicinal herb cropping system. Among the four fertilization treatments, the CF treatment resulted in the highest TP concentrations. Both biochar treatments (CFRB and CFCB) significantly reduced TP concentrations compared to CF. In the tea plantation, CFRB and CFCB reduced TP concentrations by 15.6 % and 26.9 %, respectively, while in the medicinal herb cropping system, the reductions were 15.5 % and 20.2 %, respectively.

For different P fractions, the proportions of DTP and PP in TP varied across systems. In the tea plantation, DTP and PP accounted for 53.8 % and 46.2 % of TP, respectively, whereas in the medicinal herb cropping system, these proportions were 55.1 % and 44.9 %, respectively (Fig. 2). CP concentrations ranged from 0.12 to 0.50 mg L^{-1} in the tea plantation and from 0.07 to 0.69 mg L^{-1} in the medicinal herb cropping system, representing 41.4 % and 29.7 % of the average TP concentrations, respectively. CP concentrations were notably high during periods of peak P loss following fertilization. Both biochar treatments significantly reduced CP concentrations compared to CF in both cropping systems. CFRB reduced CP concentrations by 26.1 % and 27.8 % in the tea and medicinal herb cropping systems, respectively, while CFCB reduced CP concentrations by 27.3 % and 30.4 %. There was no significant difference in CP reduction between the two biochar treatments, indicating their similar effectiveness in mitigating P loss (Fig. 2).

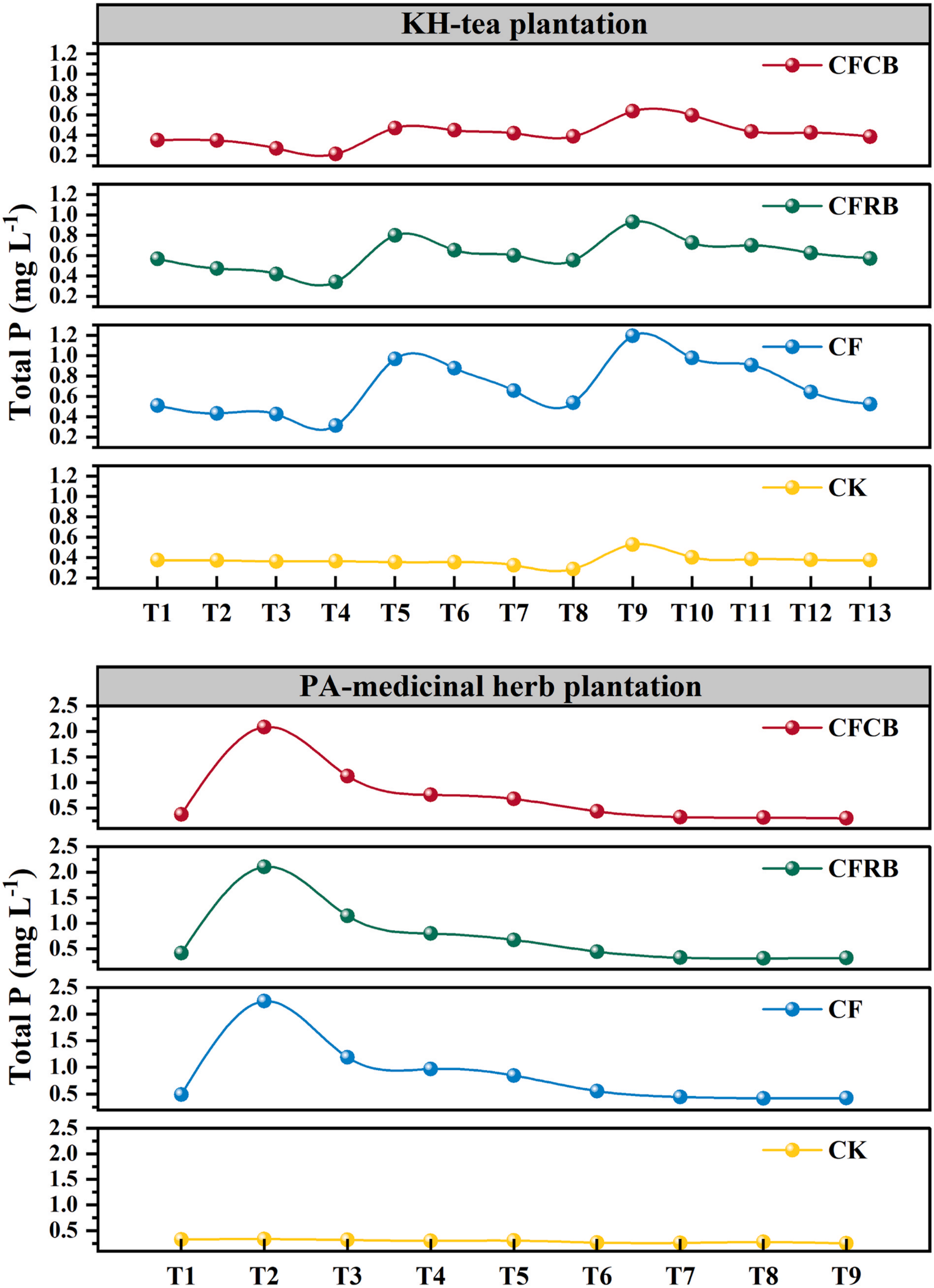

Fig. 1. Variations of total phosphorus in the runoff under different systems.

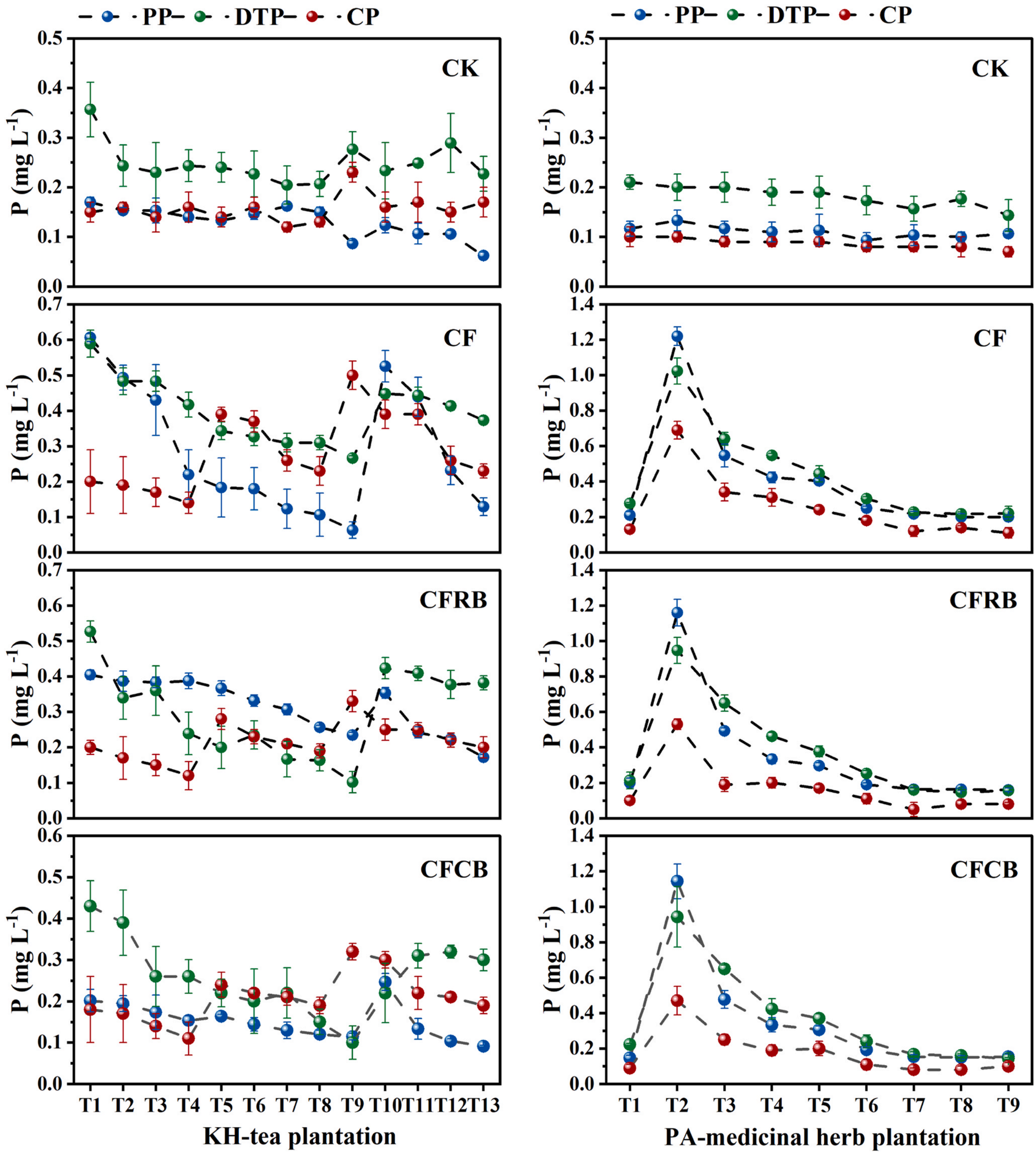

Fig. 2. Variations of particulate phosphorus (PP), dissolved toal phosphorus (DTP), and colloidal phosphorus (CP) in the runoff under different cropping systems.

3.3. *Phosphorus loss load in the runoff*

The P loss loads for different P forms in the runoff are summarized in Table 2. Overall, the cumulative TP loss in runoff was higher in the medicinal herb cropping system compared to the tea cropping system. The CF treatment resulted in the highest P loss loads, while both CFRB and CFCB treatments significantly reduced the TP loss across all forms ($p < 0.05$). However, no significant differences were observed between the two biochar treatments in terms of their effect on P loss.

In the tea cropping system, the CF produced the highest cumulative TP runoff loss, with biochar amendments effectively reducing TP loss. The DTP loss load ranged from 55.1 % to 65.1 %, PP ranged from 19.5 % to 45.5 %, and CP ranged from 35.7 % to 43.7 %. The TP runoff loss coefficient for CF was 3.5 %, while it decreased to 3.0 % and 2.0 % under CFRB and CFCB, respectively.

In the medicinal herb cropping system, CF also resulted in the highest TP runoff loss, with a cumulative loss of 2.88 kg ha^{-1} . CFRB and CFCB treatments reduced TP runoff loss by 17.0 % and 24.3 %, respectively. The proportions of DTP, PP, and CP loss in the runoff were 50.2 %–62.6 %, 37.4 %–49.8 %, and 31.8 %–33.0 %, respectively. TP runoff

Table 2
Loss load of toal phosphorus (TP), colloidal phosphorus (CP), dissolved toal phosphorus (DTP), and particulate phosphorus (PP) in the cropping systems.

Site	Treatments	TP loss load (kg ha^{-1})	CP loss load (kg ha^{-1})	DTP loss load (kg ha^{-1})	PP loss load (kg ha^{-1})
KH	CK	0.88d	0.39d	0.48c	0.40c
	CF	1.56a	0.67a	0.86a	0.70a
	CFRB	1.35b	0.59b	0.80b	0.55b
	CFCB	1.26c	0.45c	0.82b	0.24d
PA	CK	1.07c	0.34c	0.67c	0.40c
	CF	2.88a	0.97a	1.47a	1.41a
	CFRB	2.39b	0.76b	1.20b	1.19b
	CFCB	2.18b	0.72b	1.11b	1.07b

Note: KH is the Kaihua observation site; PA is the Panan observation site. Lowercase letters represent significant differences among different treatments.

loss coefficients for CF, CFRB, and CFCB were 5.76 %, 4.78 %, and 4.36 %, respectively. It is worth noting that despite the high P application during the herb cultivation season, the low rainfall during this period resulted in a small amount of runoff, and consequently, the overall P loss was relatively low.

3.4. Changes of organic carbon and pH in soil

Fertilization treatments significantly enhanced SOC content throughout the monitoring period (Fig. 3). SOC levels varied markedly among cropping systems, with the medicinal herb cropping system exhibiting the highest SOC content, ranging from 16.98 to 21.89 g kg^{-1} , significantly exceeding those observed in other systems. This increase can be attributed to higher organic matter inputs in the medicinal herb cropping system, which promoted greater carbon storage in the soil. In contrast, the tea cropping system exhibited lower SOC levels, ranging

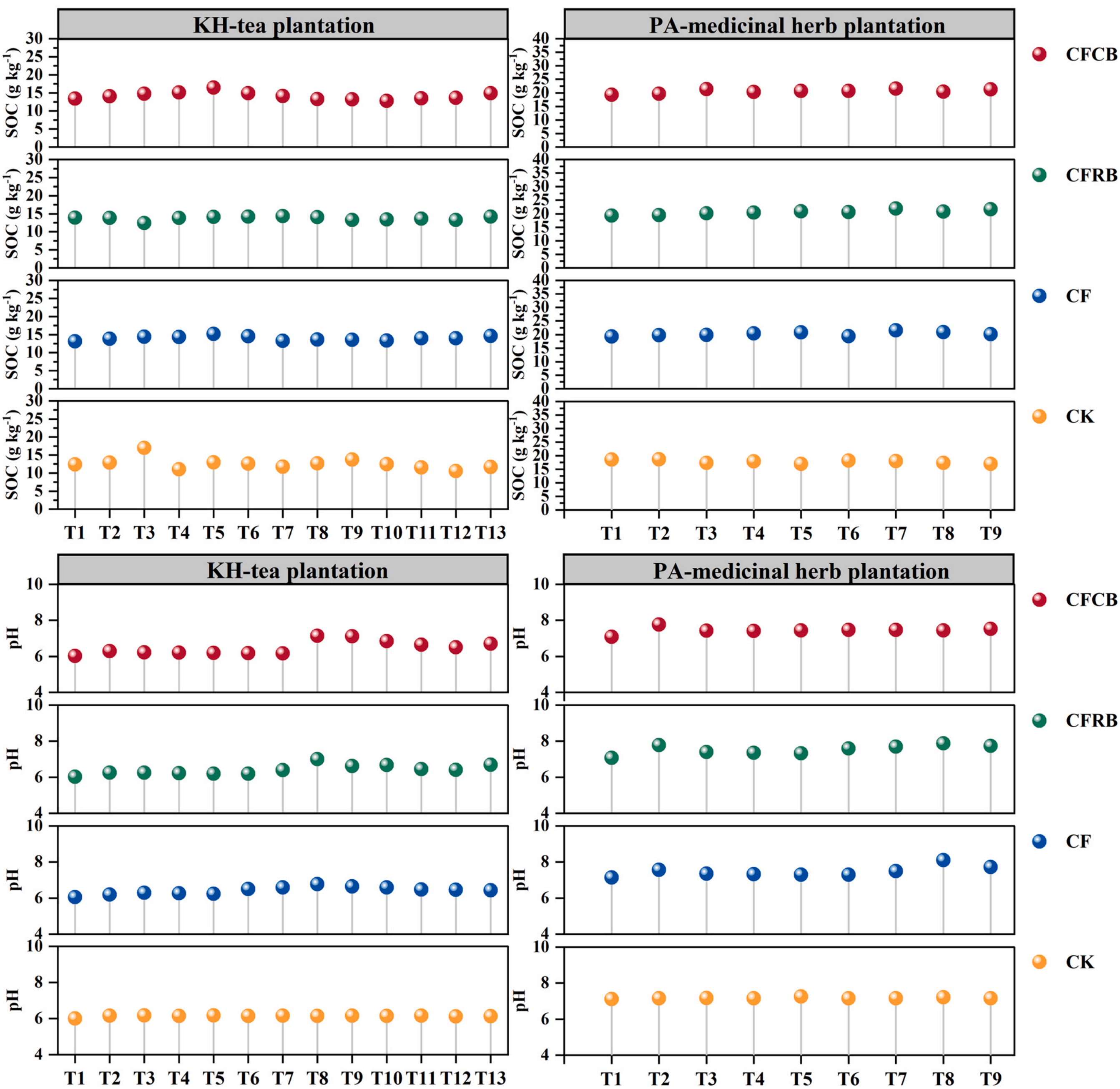

Fig. 3. Variations of soil organic carbon (SOC) and pH under different systems.

from 10.57 to 15.16 g kg^{-1} . The differences in crop type and management practices across systems played a crucial role in determining SOC accumulation. Biochar amendments (CFRB and CFCB) significantly increased SOC content and carbon storage during the early stages of the monitoring period. However, as time progressed, the differences in SOC content between the biochar treatments and CF gradually diminished.

Soil pH values fluctuated within specific ranges across different treatments (Fig. 3). In the tea cropping system, soil pH ranged from 6.02 to 7.12, indicating weakly acidic conditions. In comparison, the medicinal herb cropping system exhibited higher pH values, ranging from 7.07 to 8.10. Fertilization treatments significantly increased soil pH compared to CK, with the biochar treatments showing a more pronounced effect on pH improvement.

3.5. Phosphorus stocks and changes in soil aggregate distribution

At the end of the growing season, soil P content was analyzed (Fig. 4a–b). The tea and medicinal herb cropping systems had higher TP contents, with average values of 1120.7 mg kg^{-1} and 1320.4 mg kg^{-1} , respectively. Fertilization treatments significantly increased TP content, with all treatments showing significantly higher TP levels compared to CK. The soil in both the tea and medicinal herb cropping systems had

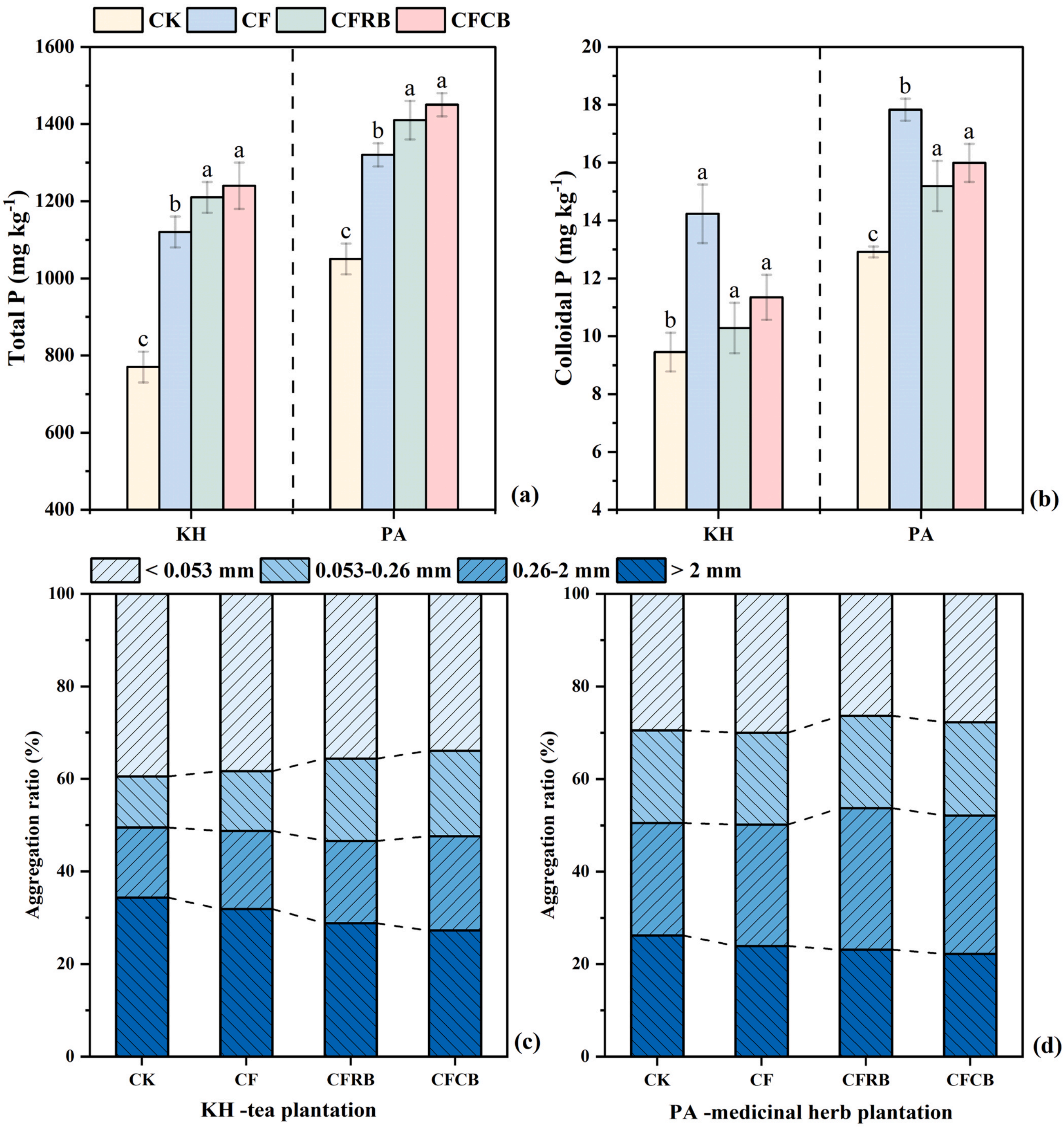

Fig. 4. (a) Total phosphorus in the soil. (b) Colloidal phosphorus in the soil. (c-d) Effects of different treatments on the soil aggregation fractions. Lowercase letters represent significant differences among different treatments.

higher CP concentrations, which accounted for 1.2 %–1.3 % of TP. Compared to CF, both CFRB and CFCB treatments reduced soil CP content. In the tea and medicinal herb cropping systems, CFRB and CFCB treatments reduced CP content by 27.8 % and 20.3 %, respectively, and by 14.8 % and 10.3 %, respectively.

Fig. 4c-d illustrates the distribution of soil aggregates across different treatments after the monitoring period. The distribution of soil aggregates was closely associated with soil texture. Compared to CF, both CFRB and CFCB treatments improved soil aggregation. The proportion of fine particles, including clay and silt (<0.053 mm), decreased by 2.3 %–4.5 %, while the total proportion of small aggregates (0.26–2 mm) and micro-aggregates (0.053–0.26 mm) increased by 3.7 %–9.0 %. These changes indicate that biochar amendments enhanced soil structure by promoting the formation of soil aggregates. In addition, there was no significant difference in crop yield between the fertilization treatments in the two systems at the end of the season (Table S4).

4. Discussion

4.1. Phosphorus loss concentration and load in runoff

P loss dynamics in surface runoff are governed by fertilization regimes, cropping system characteristics, and rainfall patterns (Du et al., 2021; Udawatta et al., 2006). Compared to paddy soils with runoff coefficients exceeding 30 % due to saturation and poor infiltration (Li et al., 2021a), tea and medicinal herb cropping systems exhibited lower runoff coefficients (8.5 % and 20.3 %, respectively) owing to greater soil permeability and retention capacities. However, under conditions of high-intensity rainfall or disrupted soil structure caused by frequent wet-dry cycles, tea and medicinal herb cropping systems may still exhibit significant P mobility in surface runoff (Huang et al., 2023).

Among the two cropping systems, the tea cropping system exhibited significantly lower P losses compared to the medicinal herb cropping system, primarily due to its lower runoff coefficients and higher soil aggregation. The clay loam soil in the tea plantation promoted better water infiltration and aggregate stability, which reduced surface runoff. Additionally, the perennial vegetation and terrace-based cultivation in the tea plantation slowed water flow, further enhancing infiltration and minimizing runoff. In contrast, the sandy soil in the medicinal herb cropping system, with its lower water-holding capacity and weaker aggregate stability, contributed to greater runoff volumes. Combined with higher fertilization rates, this led to significantly higher P loss loads in the medicinal herb cropping system. These results align with studies on vegetable systems, where high P inputs and soil properties that reduce P retention exacerbate P mobility and losses (Wang et al., 2019b).

In both systems, P losses peaked within one week of fertilizer application, highlighting the vulnerability of early-season rainfall events. The study by Hua et al. (2019) attributed early-season P loss to the release of DTP fractions from base fertilizers during rainfall events. Notably, CP accounted for 41.4 % and 29.7 % of TP in the tea and medicinal herb cropping systems, respectively, underscoring its significant contribution to TP loss in these cropping systems. While these CP proportions are comparable to those reported for paddy soils (~40 %), they exceed values observed in vegetable systems (~20 %). The higher CP proportion in the tea plantation may be attributed to stronger micro-aggregation and a higher proportion of fine clay particles, which serve as nuclei for colloid formation. In contrast, the medicinal herb cropping system, characterized by sandy soil textures and lower aggregation, likely limits the retention of CP, resulting in its reduced proportion relative to TP.

4.2. Effectiveness of biochar in reducing phosphorus loss and improving soil properties

In this study, straw-derived biochar significantly reduced P concentrations in runoff compared with CF, with CP losses decreasing by up to 30.4 %. This effect is partly due to biochar replacing a portion of the soluble P in chemical fertilizers, thereby lowering the immediate pool of mobile P. The comparable effects of these two biochars on P loss and soil properties can be attributed to their shared plant-derived origin and similar organic structures.

Mechanistically, biochar reduced CP transport through both physical and chemical pathways. Physically, biochar improved soil aggregation by enhancing the formation of small and microaggregates, as evidenced by the decreased proportion of fine particles (<0.053 mm) and increased aggregate stability. Improved soil aggregation effectively limits the detachment and transport of colloidal and particulate P, aligning with previous studies that highlight biochar's role in promoting aggregate stability (Lee et al., 2015).

Chemically, the observed increases in SOC, particularly in the medicinal herb cropping system, further contributed to P retention. Biochar's porous structure and surface functional groups enhance P adsorption and aggregation mechanisms, adsorbing and fixing free phosphate ions (Laird et al., 2010). However, the relationship between SOC and P dynamics is multifaceted. On one hand, the increased organic carbon introduced by biochar can elevate negative charges and P adsorption saturation of colloidal particles (Li et al., 2019b), potentially destabilizing certain P-bound colloids and influencing their transport through the soil. Yan et al. (2017) demonstrated that dissolved organic matter could form soluble Fe-organic complexes, thereby reducing the Fe-bound colloidal P fraction. On the other hand, soil organic matter plays a critical role in stabilizing soil structure by forming clay-organic matter complexes, which contribute to aggregate stability and limit colloidal transport (Li et al., 2019).

Soil pH increased significantly under biochar treatments, particularly in the tea cropping system, which had an initial pH in the acidic range. Hens et al. (2002) found that an increase in pH reduces H^+ competition for adsorption sites, causing partial desorption of colloids and reducing CP concentrations. The phosphate-binding capacity of Fe oxides decreased with increasing pH (5–8) due to reduced competition with hydroxyl ions (Schönbrunner et al., 2012). Furthermore, biochar's ability to increase pH reduced the availability of exchangeable H^+, Al^{3+}, and Fe^{3+}, which otherwise enhanced P adsorption (Li et al., 2019a). However, the effects of biochar on soil pH are soil-dependent. For instance, Li et al. (2018) reported no significant pH changes in semi-arid soils following biochar application, and Werner et al. (2018) found that biochar amendments did not alter the pH of sandy loam soils. In this study, the effect of biochar on increasing soil pH diminished over time, possibly due to buffering by native soil minerals or leaching. From a practical perspective, both rice and corn straw biochars offer sustainable reuse pathways for agricultural waste while providing agronomic benefits. The comparable effectiveness of the two biochars in reducing P loss suggests that local availability and cost may guide biochar selection in field applications. Moreover, the observed reductions in runoff P loss without yield penalties indicate that partial substitution of chemical fertilizers with straw biochar is a feasible strategy in both perennial (tea) and annual (medicinal herb) cropping systems.

4.3. Influence factors and implications

Soil texture and aggregation emerged as key determinants of P loss pathways in this study (Chen and Arai, 2020; Li et al., 2021b). Higher TP loss loads in the medicinal herb cropping system were closely associated with higher P inputs and low clay content. Sandy soils lack the charge density and micropore structure needed to retain CP, leading to greater nutrient transport. Excessive P inputs lead to saturation of soil adsorption sites (Fischer et al., 2018) and increased P mobility.

Biochar-induced improvements in soil aggregation reduced the proportion of fine particles and increased the stability of small and micro-aggregates, effectively mitigating CP and TP losses. These findings align with studies suggesting that soil structural improvements enhance P retention and reduce colloid-facilitated transport (Li et al., 2021a; Li et al., 2021b). Stable aggregates physically protect colloidal particles and reduce the connectivity of preferential flow paths, thus lowering the risk of CP mobilization.

Pearson correlation analysis further revealed significant associations between SOC, pH, and P loss patterns (Fig. 5). However, the relationship between SOC and soil aggregation presents a nuanced dynamic. On one hand, increased SOC input may elevate the formation of colloidal particles (Li et al., 2019). On the other hand, higher SOC levels can enhance soil aggregate stability by forming clay-organic matter complexes, which strengthen soil structure and limit colloidal transport (Li et al., 2020b). This duality suggests that the effects of SOC on P loss are non-linear and depend on the balance between colloid formation and aggregate stabilization. Future research should aim to clarify these competing mechanisms, particularly under varying SOC input levels and soil textures.

The two cropping systems in the study differ not only in soil properties but also in planting patterns and management intensity. Tea, as a perennial crop, is typically grown on sloped terraces with permanent vegetation cover, contributing to more stable soil structure and reduced surface runoff. In contrast, medicinal herbs are cultivated as annual or short-cycle crops with frequent tillage and higher fertilizer input, which may weaken aggregation and increase P mobilization. Future research should expand to include a broader range of cropping systems to better understand how planting modes, disturbance regimes, and nutrient management interact to influence P mobility behavior. Moreover, although existing literature suggests that wetting–drying cycles can disrupt soil microstructure and enhance CP mobilization (Mohanty et al., 2016; Gu et al., 2018; Wang et al., 2024), these effects were not directly measured in the current study. Therefore, future studies should further explore the interactions between soil moisture regimes, microbial activity, and CP transport across different land uses and climatic conditions.

5. Conclusion

This study demonstrated the effectiveness of rice straw and corn straw biochar amendments in reducing P loss and improving soil properties in tea and medicinal herb cropping systems. The tea cropping system, exhibited a lower P loss load due to its higher soil aggregation and lower runoff coefficients, while the medicinal herb cropping system experienced greater P loss driven by sandy soils, more disturbance, and higher fertilization rates. Straw biochar amendments effectively reduced TP and CP losses by improving soil structure, increasing SOC levels, and raising soil pH. These improvements increased the proportion of small and micro-aggregates, limited P detachment, and reduced colloid-facilitated transport. This study addresses a critical gap in understanding P loss mechanisms in tea and medicinal herb cropping systems, providing evidence for biochar's role in mitigating P loss and enhancing soil aggregation. Nevertheless, the findings were based on one-year monitoring from two field sites. Future work should prioritize long-term field monitoring across diverse soils, climates, and cropping systems to evaluate the cumulative effects of biochar and support more tailored nutrient management strategies.

CRediT authorship contribution statement

Xinqiang Liang: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Kejin Zhou:** Investigation, Formal analysis. **Shuang He:** Writing – review & editing, Data curation, Conceptualization. **Weidong Feng:** Writing – review & editing, Investigation. **Ziwan Wang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Data curation, Conceptualization. **Chunlong Liu:** Writing – review & editing, Investigation, Data curation. **Fayong Li:** Writing – review & editing, Validation, Investigation, Formal analysis.

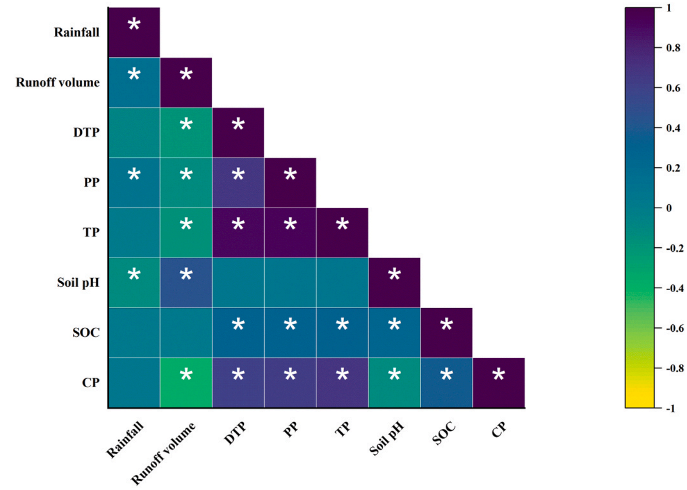

Fig. 5. Pearson correlation coefficients of phosphorus forms (total phosphorus, particulate phosphorus, dissolved toal phosphorus, and colloidal phosphorus) with other parameters (soil organic carbon, pH, rainfall, and runoff volume). Mark represents $p < 0.05$.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109824.

Data availability

Data will be made available on request.

References

Bao, S., 2000. Soil Agrochemical Analysis. China Agricultural Press, Beijing, pp. 265–267.
Ch'Ng, H.Y., Ahmed, O.H., Majid, N.M.A., 2014. Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. Sci. World J., 506356
Chen, A., Arai, Y., 2020. Current uncertainties in assessing the colloidal phosphorus loss from soil. Adv. Agron. 163, 117–151.
Du, Y., Li, T., He, B., 2021. Runoff-related nutrient loss affected by fertilization and cultivation in sloping croplands: an 11-year observation under natural rainfall. Agric. Ecosyst. Environ. 319, 107549.
FAO. 2022. FAOSTAT Online Statistical Service. Food and Agricultural Organization of the United Nations Rome.
Fischer, P., Pöthig, R., Gücker, B., Venohr, M., 2018. Phosphorus saturation and superficial fertilizer application as key parameters to assess the risk of diffuse phosphorus losses from agricultural soils in Brazil. Sci. Total Environ. 630, 1515–1527.
García-Gaines, R.A., Frankenstein, S., 2015. USCS and the USDA Soil Classification System: Development of A Mapping Scheme.

Gu, S., Gruau, G., Malique, F., Dupas, R., Petitjean, P., Gascuel-Odoux, C., 2018. Drying/rewetting cycles stimulate release of colloidal-bound phosphorus in riparian soils. Geoderma 321, 32–41.
Hens, M., Merckx, R., 2002. The role of colloidal particles in the speciation and analysis of "dissolved" phosphorus. Water Res. 36, 1483–1492.
Hua, L., Zhai, L., Liu, J., Liu, H., Zhang, F., Fan, X., 2019. Effect of irrigation-drainage unit on phosphorus interception in paddy field system. J. Environ. Manag. 235, 319–327.
Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang, L., Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., Yan, H., Wang, G., 2017. Dryland climate change: recent progress and challenges. Rev. Geophys. 55 (3), 719–778.
Huang, X., Zhen, D., Lu, X., Zhang, Y., Liu, Y., Li, Y., Jiang, T., 2023. Nitrogen and phosphorus losses via surface runoff from tea plantations in the mountainous areas of Southwest China. Plos One 18 (6), e0285112.
Laird, D., Fleming, P., Wang, B., Horton, R., Karlen, D., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158 (3-4), 436–442.
Lee, S.S., Shah, H.S., Awad, Y.M., Kumar, S., Ok, Y.S., 2015. Synergy effects of biochar and polyacrylamide on plants growth and soil erosion control. Environ. Earth Sci. 74, 2463–2473.
Li, F., Jin, Y., He, S., Jin, J., Wang, Z., Khan, S., Tian, G., Liang, X., 2021a. Use of polyacrylamide modified biochar coupled with organic and chemical fertilizers for reducing phosphorus loss under different cropping systems. Agric. Ecosyst. Environ. 310, 107306.
Li, F., Liang, X., Niyungeko, C., Sun, T., Liu, F., Arai, Y., 2019. Effects of biochar amendments on soil phosphorus transformation in agricultural soils. Adv. Agron. 158, 131–172.
Li, C., Xiong, Y., Qu, Z., Xu, X., Huang, Q., Huang, G., 2018. Impact of biochar addition on soil properties and water-fertilizer productivity of tomato in semi-arid region of Inner Mongolia, China. Geoderma 331, 100–108.
Li, F., Zhang, Q., Klumpp, E., Bol, R., Nischwitz, V., Ge, Z., Liang, X., 2021b. Organic carbon linkage with soil colloidal phosphorus at regional and field scales: insights from size fractionation of fine particles. Environ. Sci. Technol. 55 (9), 5815–5825.
Liang, X., Liu, J., Chen, Y., Li, H., Ye, Y., Nie, Z., Su, M., Xu, Z., 2010. Effect of pH on the release of soil colloidal phosphorus. J. Soils Sediment. 10, 1548–1556.
Madiba, O.F., Solaiman, Z.M., Carson, J.K., Murphy, D.V., 2016. Biochar increases availability and uptake of phosphorus to wheat under leaching conditions. Biol. Fertil. Soils 52, 439–446.
Missong, A., Bol, R., Nischwitz, V., Krüger, J., Lang, F., Siemens, J., Klumpp, E., 2018. Phosphorus in water dispersible-colloids of forest soil profiles. Plant Soil 427, 71–86.
Mohanty, S.K., Saiers, J.E., Ryan, J.N., 2016. Colloid mobilization in a fractured soil: effect of pore-water exchange between preferential flow paths and soil matrix. Environ. Sci. Technol. 50 (5), 2310–2317.
Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.
Ni, K., Liao, W., Yi, X., Niu, S., Ma, L., Shi, Y., Zhang, Q., Liu, M., Ruan, J., 2019. Fertilization status and reduction potential in tea gardens of China. J. Plant Nutr. Fertil. 25 (3), 421–432.
Olsen, S.R., Sommers, L.E., 1982. Phosphorus.
Sato, J.H., Figueiredo, C.C.D., Marchão, R.L., Madari, B.E., Benedito, L.E.C., Busato, J.G., Souza, D.M.D., 2014. Methods of soil organic carbon determination in Brazilian savannah soils. Sci. Agric. 71, 302–308.
Schönbrunner, I.M., Preiner, S., Hein, T., 2012. Impact of drying and re-flooding of sediment on phosphorus dynamics of river-floodplain systems. Sci. Total Environ. 432, 329–337.
Siebers, N., Kruse, J., Jia, Y., Lennartz, B., Koch, S., 2023. Loss of subsurface particulate and truly dissolved phosphorus during various flow conditions along a tile drain–ditch–brook continuum. Sci. Total Environ. 866, 161439.
Sowers, T.D., Holden, K.L., Coward, E.K., Sparks, D.L., 2019. Dissolved organic matter sorption and molecular fractionation by naturally occurring bacteriogenic iron (oxyhydr) oxides. Environ. Sci. Technol. 53 (8), 4295–4304.
Udawatta, R.P., Motavalli, P.P., Garrett, H.E., Krstansky, J.J., 2006. Nitrogen losses in runoff from three adjacent agricultural watersheds with claypan soils. Agric. Ecosyst. Environ. 117 (1), 39–48.
Wan, W., Li, X., Han, S., Wang, L., Luo, X., Chen, W., Huang, Q., 2020. Soil aggregate fractionation and phosphorus fraction driven by long-term fertilization regimes affect the abundance and composition of P-cycling-related bacteria. Soil Tillage Res. 196, 104475.
Wang, Z., Chen, L., Liu, C., Jin, Y., Li, F., Khan, S., Liang, X., 2021. Reduced colloidal phosphorus loss potential and enhanced phosphorus availability by manure-derived biochar addition to paddy soils. Geoderma 402, 115348.
Wang, Z., Eltohamy, K.M., Liu, B., Jin, J., Liang, X., 2024. Effects of drying-rewetting cycles on colloidal phosphorus composition in paddy and vegetable soils. Sci. Total Environ. 907, 168016.
Wang, L., Jiao, W., MacBean, N., Rulli, M.C., Manzoni, S., Vico, G., D'Odorico, P., 2022. Dryland productivity under a changing climate. Nat. Clim. Change 12 (11), 981–994.
Wang, R., Min, J., Kronzucker, H.J., Li, Y., Shi, W., 2019b. N and P runoff losses in China's vegetable production systems: loss characteristics, impact, and management practices. Sci. Total Environ. 663, 971–979.
Wang, L., Zhao, X., Gao, J., Butterly, C.R., Chen, Q., Liu, M., Yang, Y., Xi, Y., Xiao, X., 2019a. Effects of fertilizer types on nitrogen and phosphorous loss from rice-wheat rotation system in the Taihu Lake region of China. Agric. Ecosyst. Environ. 285, 106605.
Warrinnier, R., Goossens, T., Amery, F., Nest, T.V., Verbeeck, M., Smolders, E., 2019. Investigation on the control of phosphate leaching by sorption and colloidal transport: column studies and multi-surface complexation modelling. Appl. Geochem. 100, 371–379.
Werner, S., Kätzl, K., Wichern, M., Buerkert, A., Steiner, C., Marschner, B., 2018. Agronomic benefits of biochar as a soil amendment after its use as waste water filtration medium. Environ. Pollut. 233, 561–568.
Yan, J., Jiang, T., Yao, Y., Wang, J., Cai, Y., Green, N.W., Wei, S., 2017. Underestimation of phosphorus fraction change in the supernatant after phosphorus adsorption onto iron oxides and iron oxide–natural organic matter complexes. J. Environ. Sci. 55, 197–205.