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Optimizing Biochar Concentration for Mitigating Nutrient Losses in Runoff: An Investigation into Soil Quality Improvement and Non-Point Source Pollution Reduction

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Abstract: Rainfall runoff can lead to a reduced soil quality and non-point source pollution through the removal of nutrients from the topsoil that are not utilized by plants. The use of biochar is an effective method to solve this problem. The aim of this study was to determine the optimal concentration of added biochar to reduce the soil particle, NH_4^+ -N (AN), NO_3^- -N (NN), and total phosphorus (TP) losses. Additionally, the inhibitory mechanisms of biochar that mitigate nutrient loss were revealed using FT-IR (Fourier-transform infrared) spectrometry and SEM (scanning electron microscopy). Compared with the control group, the addition of 2% biochar resulted in decreases in the AN, NN, TP, and soil erosion rates of 57.08%, 4.25%, 30.37%, and 22.78%, respectively; the leaching loss rates of AN and NN were reduced by 6.4% and 9.87%, respectively. However, it should be noted that the use of biochar resulted in an increase in the loss of soil particles smaller than 20 μm, while it resulted in a decrease in the loss of soil particles larger than 20 μm. Adsorption processes on the benzene ring may have caused the absorption peak at approximately 1600 cm^{-1} to disappear after adsorption. The porous structure of biochar and the presence of hydrophilic groups (such as hydroxyl groups) facilitate adsorption reactions. The optimal concentration of added biochar was 2%.

Keywords: biochar; soil size; ammonia nitrogen loss; nitrate loss; total phosphorus loss

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Academic Editor: Shiqiang Wei

Received: 29 November 2024
Revised: 25 December 2024
Accepted: 26 December 2024
Published: 27 December 2024

Citation: Xing, L.; Niu, X.; Yin, X.; Duan, Z.; Liu, A.; Ma, Y.; Gao, P. Optimizing Biochar Concentration for Mitigating Nutrient Losses in Runoff: An Investigation into Soil Quality Improvement and Non-Point Source Pollution Reduction. *Agriculture* **2025**, *15*, 45. https://doi.org/10.3390/agriculture15010045

1. Introduction

Phosphorus and nitrogen are two essential nutrients for all living organisms on Earth [1]. They are naturally present in various types of soil, and nitrogen exists in different forms and can be easily transported and transformed. In contrast, phosphorus is a mineral resource that is crucial for maintaining agricultural productivity [2]. Regarding plant growth, nitrogen and phosphorus are essential nutrients that play an integral role in food cultivation and upkeep [3,4]. Surface runoff occurs whenever the rainfall rate exceeds the soil's water infiltration rate; this flow carries soil particles, as well as nitrogen and phosphorus, from the topsoil. The buildup of these nutrients in aquatic environments causes eutrophication. Soil loss not only reduces the amount of arable land available but also elevates water levels in rivers and lakes, negatively impacting crop cultivation. Surface water drainage and leaching processes can cause excessive losses of organic phosphorus, which exacerbate the related problems and pose risk to human health and livelihoods [2].

Phosphorus easily migrates with surface runoff because it can combine with other ions to form insoluble compounds and then precipitate from the solution [5]. Excessive nitrogen in water can be harmful to fish and may even cause mass fish deaths. Additionally, the growing rates of agricultural phosphorus runoff and leaching losses have raised concerns about water contamination [6]. On the other hand, precipitation can cause phosphate and nitrogen to leach. It was previously thought that the leaching of phosphorus through the soil profile was insignificant or that leaching rarely occurred. However, excessive use of fertilizers can cause phosphorus to accumulate in the soil, which can then leak out during irrigation or rainfall [7]. Therefore, it is important to develop effective strategies to reduce soil, phosphate, and nitrogen losses.

Incorporating adsorbent materials into soil is frequently used due to its low cost, high efficiency, and simple application [8]. Biochar, a stable porous carbonaceous solid produced from biomass through thermochemical transformation in an oxygen-limited environment, has the potential to increase soil fertility and stimulate soil microbial activity [9,10]. It has a high carbon content, a large specific surface area, a complex pore structure, surface functional groups, strong adsorption ability, and stable physicochemical properties. Due to these characteristics, it has gained significant attention for its excellent performance in soil improvement, carbon sequestration, emission reduction, and environmental remediation [11]. Therefore, it plays a vital role in reducing non-point pollution from agriculture [7]. Biochar addition may reduce ammonia nitrogen loss, according to Zhang et al. (2021) [12]. A variety of raw materials, such as wood-based materials, agricultural waste, various grasses, and manure/biosolids, could be made into biochar. Different raw materials can cause significant differences in the elemental and mineral compositions of biochar [13]. China produces approximately 900,000 tons of agricultural straw annually, with maize straw accounting for 32.5% [3]. Yadav et al. (2019) suggested that converting organic waste into biochar is a viable method for reducing nutrient loss, cutting costs, and enhancing plant production [14]. However, it is crucial to appropriately add biochar to reduce nutrient runoff and leaching loss. The rate of biochar addition varies depending on the soil type. Li et al. (2022) found a positive correlation between the application rate of biochar and the reduction in nitrogen leaching [3]. Some studies have found that soil treated with biochar can increase P retention and reduce the risk of P loss [2,6,15–17]. Additionally, the addition of biochar can effectively mitigate soil erosion [18,19]. However, the improper addition of biochar can also increase the risk of nutrient loss. Excessive biochar application can result in nitrogen leaching, as reported by C. Zhang et al. (2021) [20]. Li et al. (2019) found that higher rates of biochar addition ($\geq$5%) promoted soil loss, while lower rates ($\geq$3%) had limited effects [21].

Under natural conditions, the effects of biochar on erosion are complex [22]. Currently, many studies are focused on the ability of biochar to inhibit nitrogen and phosphorus losses. However, few studies have explored its ability to simultaneously mitigate nitrogen, phosphorus, and soil particle losses in runoff, as well as nitrogen and phosphate losses through soil leaching. This study conducted slope simulation experiments and soil column leaching experiments, accompanied by SEM and FT-IR analyses, to investigate the effects of the adsorption mechanisms of biochar on nutrient loss. Therefore, the research objective was to find suitable concentrations of biochar to reduce the loss of AN, NN, TP, and soil particles due to runoff and the loss of AN, NN, and TP with leaching. In addition, this study examined the influence of different amounts of biochar addition on the particle size of the eroded soil and elucidated the mechanisms and functional groups involved in biochar adsorption.

2. Materials and Methods

Corn straw was used as the raw material for biochar production. The process involved oxygen-limited heating at a temperature of 500 °C and was conducted by Henan Lize Environmental Protection Technology Co., LTD. The biochar passed through a 100-mesh sieve. Soil samples were collected from a planting region located at the coordinates 117.99555° E and 36.81088° N in Zibo, Shandong Province, China, using the five-point sampling method described in [23]. The main soil use type in this area is deciduous broad-leaved forest land. The soil texture is silt sand. Soil samples were collected in the summer at a distance of 1–20 cm from the surface layer [24]. After removing visible stones, plant roots, and other debris, the soil was air-dried in a cool and well-ventilated area. All experiments were conducted using environmental science analysis. The physical and chemical properties of the soil and the biochar are shown in Tables 1 and 2, respectively. The NN content was determined using ultraviolet spectrophotometry, while photometry was used to determine the AN content. Soil pH was measured using a pH meter at a soil-to-water ratio of 1:1, and TP levels were determined using the persulfate digestion method. The soil samples were oxidized with potassium dichromate and analyzed using spectrophotometry to determine the organic matter content [25]. The soil particle size was analyzed using a laser particle size analyzer (RTse2006 laser particle size analyzer).

Table 1. Initial physicochemical properties of soils used in this study.

pH	AN (mg/kg)	NN (mg/kg)	TP (mg/kg)	TOC (g/kg)	Bulk Density (g/cm^3)	Clay (<0.002 mm)	Silt (0.05~0.002 mm)	Sand (>0.05 mm)
7.55 ± 0.10	4.23 ± 0.12	9.27 ± 0.29	117.46 ± 0.93	18.01 ± 0.25	1.18 ± 0.09	0.11 ± 0.01%	99.01 ± 1.12%	0.88 ± 0.02%

Table 2. Initial physicochemical properties of biochar used in this study.

pH	Electrical Conductivity (mS/cm)	Ash Content (%)	Elemental Content				
			C (%)	N (%)	O (%)	S (%)	P (%)
10.04	1.22	2.89	71.58	0.05	12.30	0.21	6.72

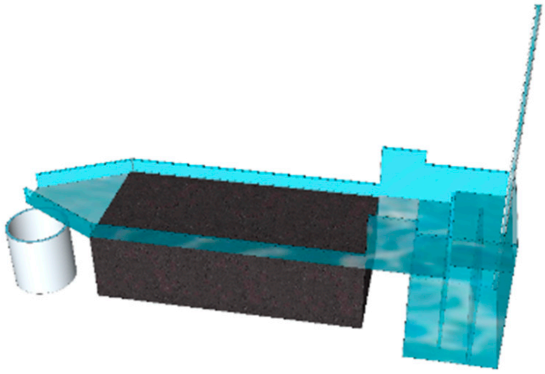
2.1. Slope Simulation Experiment

To investigate the optimal concentration of biochar for mitigating the runoff losses of AN, NN, TP, and soil particles, three experimental groups were established: SBC0, SBC2, and SBC4 (the amounts of biochar added in the slope experiment were 0%, 2%, and 4%). The recorded data can be found in Table 3. The slope experiment employed a water tank (0.4 m × 0.35 m × 0.3 m) and a soil box (0.9 m × 0.4 m × 0.25 m) (Figure 1a). Firstly, a 10 cm layer of pebbles was added to the bottom of the planter box to facilitate water drainage. A spray bottle was used to evenly spray water onto the mixtures and to adjust the moisture content to 12% (m%). The mixtures were placed in the soil box at a depth of 15 cm to achieve a bulk density similar to that of the natural plow layer. The soil box was then adjusted to 4° and left to settle naturally for 24 h. A water pump was used to control the flow rate at 3 L/min, and deionized water was added to the water tank. Water and sediment were collected in a plastic bucket every minute for a total of 15 min. After allowing the plastic bucket to stand for 24 h, the liquid was filtered and stored in a refrigerator at 4 °C. The concentration of ammonia nitrogen in the aqueous solution was determined using Nessler's reagent spectrophotometry [26], while the concentration of NN was measured through spectrophotometry after treatment with a macroporous adsorption resin [27]. After filtration through a 0.45 um filter membrane, the TP concentration was determined using the potassium persulfate oxidation molybdenum blue colorimetric method [28]. The sediment was dried, weighed, and analyzed for particle size using laser particle size analysis techniques. Each experimental group was replicated three times. The content of each part was calculated using Equation (1). After the experiment, the biochar was extracted [29] and characterized. The micromorphological traits of the biochar before and after the experiment were examined using SEM, while FT-IR spectroscopy was used to identify the surface functional groups.

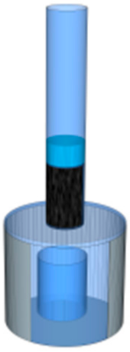
Table 3. The amounts of biochar added in the horizontal slope experiment and soil column leaching experiment.

	SBC0	SBC2	SBC4	VBC0	VBC2	VBC4
Biochar (kg)	0	1.27	2.58	0	0.023	0.046
Soil (kg)	64.25	63.45	61.92	1.14	1.12	1.09
Proportion of biochar added (m%)	0%	2%	4%	0%	2%	4%
Deionized water (L)	7.71	7.77	7.74	0.15	0.15	0.15
Moisture content	12%	12%	12%	12%	12%	12%
Bulk density (g/cm^3)	1.2	1.2	1.2	1.2	1.2	1.2
pH value	7.55	7.91	7.98	7.55	7.91	7.98

(SBC0, SBC2, and SBC4 indicate the amounts of biochar added in the slope experiment: 0%, 2%, and 4%; VBC0, VBC2, VBC4 indicate the amounts of biochar added in the leaching experiment: 0%, 2%, and 4%).



(**a**)



(**b**)

Figure 1. The device for conducting the slope simulation experiment (**a**) and the device for the soil column leaching experiment (**b**).

2.2. Soil Column Leaching Experiment

To investigate the optimal biochar concentration for preventing the leaching loss of AN, NN, and TP, three experiments were conducted: VBC0, VBC2, and VBC4 (the amounts of biochar added in the leaching experiment were 0%, 2%, and 4%). The recorded data are available in Table 3. The PVC pipe was 50 cm tall and had a diameter of 9 cm. Several small holes with a diameter of 0.5 cm were evenly distributed at the bottom of the PVC pipe (Figure 1b). To reduce edge effects, we applied a layer of petroleum jelly to the inner wall of the experimental device. We lined the device with a piece of filter paper at the bottom to prevent soil seepage. Next, we added the mixture to the device, filling it to a depth of 15 cm. We adjusted the moisture content to 12% (m%) and covered the top with plastic wrap. Finally, we left the mixture to stand for 24 h. Deionized water was added slowly along the inner wall of the device, maintaining the liquid level at approximately 1 cm above the mixture. A beaker was placed at the bottom of the device to collect the leachate, with each beaker receiving around 150 mL for each group; in total, there were 15 groups. After the 15 water samples were collected (2250 mL in total), the time taken was recorded. The experiment was repeated three times. The concentrations of AN, NN, and TP in the aqueous solution were determined using the same procedure as that used above. The contents were calculated using Equation (1). The data obtained from this experiment were significant and used for further analysis. By analyzing the cumulative loss of nutrients, the effectiveness of biochar addition can be determined.

$$M = CV \tag{1}$$

where M is the content of AN, NN, or TP in the solution; C is the concentration of AN, NN, or TP in the solution (ug/mL); and V is the volume of the solution (mL).

2.3. Characterization

The biochar's surface morphology was examined using FE-SEM (Apreo SEM, Thermo Fisher Scientific, Switzerland). To analyze and characterize the chemical surface functional groups of the biochar, FTIR spectroscopy (Thermo Electron Nicolet 5700, Thermoelectric Nickel Instruments, USA) was employed [30]. The spectral measurements covered the 650–4000 cm^{-1} wave range, providing a comprehensive examination of the biochar's chemical properties [31].

2.4. Statistical Analysis

The study employed one-way analysis of variance (ANOVA) to assess the variations among the different treatments. The least significant difference (LSD) method was used to determine the significant differences ($p < 0.05$). The statistical analyses were conducted using SPSS 22.0 and Origin 2021. SPSS 22.0 was used for the significance analyses; Origin 2021 was used to draw the charts.

3. Results

3.1. Biochar Characterization

To clarify the adsorption mechanism of corn straw biochar, SEM and FT-IR spectroscopy were used for characterization in this study. Figure 2a displays the surface characteristics before adsorption, while Figure 2b–d show the scanning results of the corn straw biochar after the adsorption process. The biochar surface exhibited numerous small particles, resulting in a rough texture. This rough texture can be attributed to the adsorption of ions and soil particles. The biochar produced from corn straw has a briquette-like structure, providing a large surface area that effectively adsorbs nitrogen, phosphorus, and soil particles.

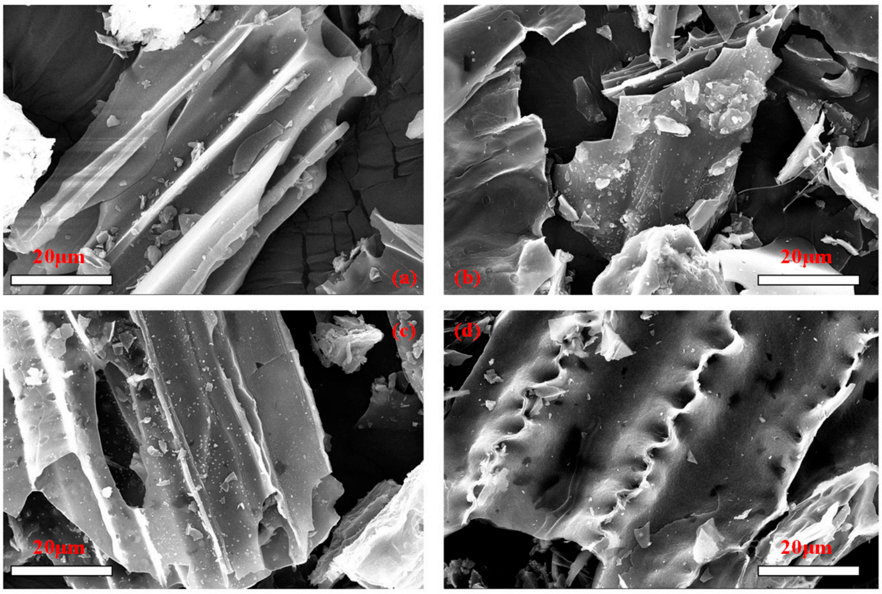


Figure 2. SEM images of corn straw biochar before adsorption (**a**) and after adsorption (**b**–**d**).

The functional groups present on the surface of the biochar were examined using FTIR spectroscopy within the 650–4000 cm^{-1} wavenumber range, as shown in the spectra in Figure 3 [32].

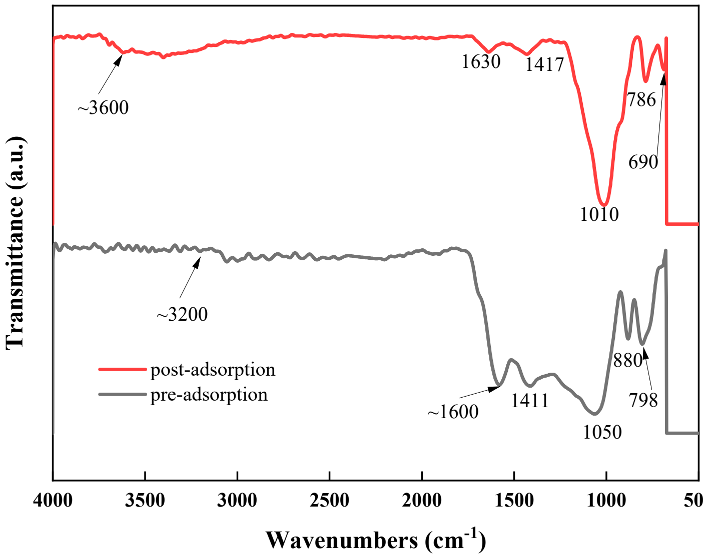


Figure 3. FTIR analysis of corn straw biochar pre- and post-adsorption.

3.2. Runoff Loss of Ammonia Nitrogen, Nitrate Nitrogen, and Total Phosphorus

Based on the data presented in Figure 4a, the concentration of ammonia nitrogen (AN) in SBC0, SBC2, and SBC4 peaked at the third minute (3.52 mg), first minute (1.85 mg), and first minute (3.69 mg), respectively. The addition of biochar resulted in a decrease in AN loss, while the control group showed an increase in AN loss. During the 15 min time frame, the combined AN loss of SBC0, SBC2, and SBC4 was 36.04 mg, 15.47 mg, and 27.96 mg, respectively (Figure 5a). SBC2 showed a 57.08% reduction in AN loss compared to SBC0, while SBC4 experienced a 22.42% reduction. As shown in Table 4, the addition of biochar can significantly reduce the cumulative loss of ammonia nitrogen.

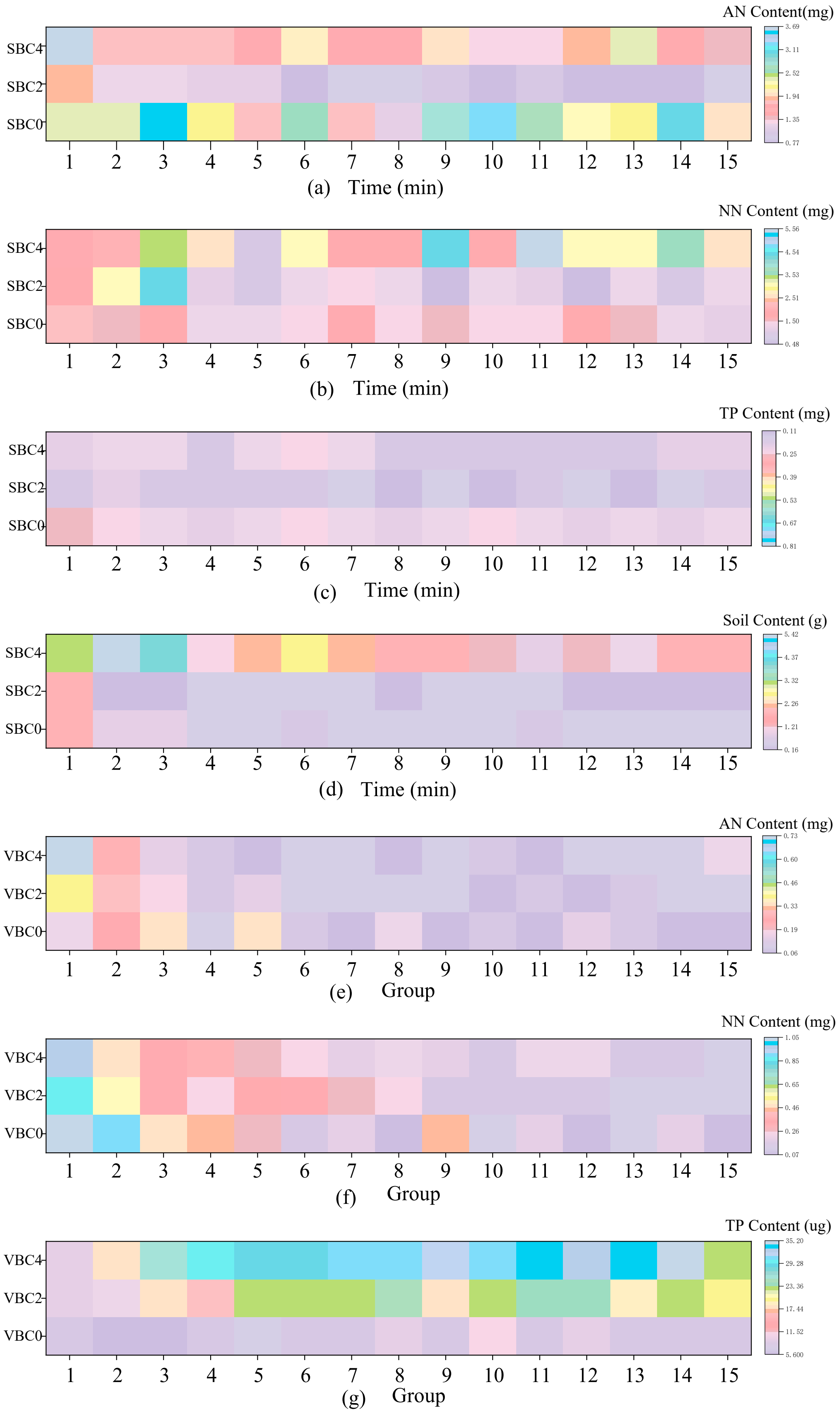


Figure 4. AN, NN, TP (**a**–**c**), and soil particle (**d**) contents of aqueous solution in slope experiment; of AN, NN, and TP contents (**e**–**g**) in aqueous solution in soil leaching experiment.

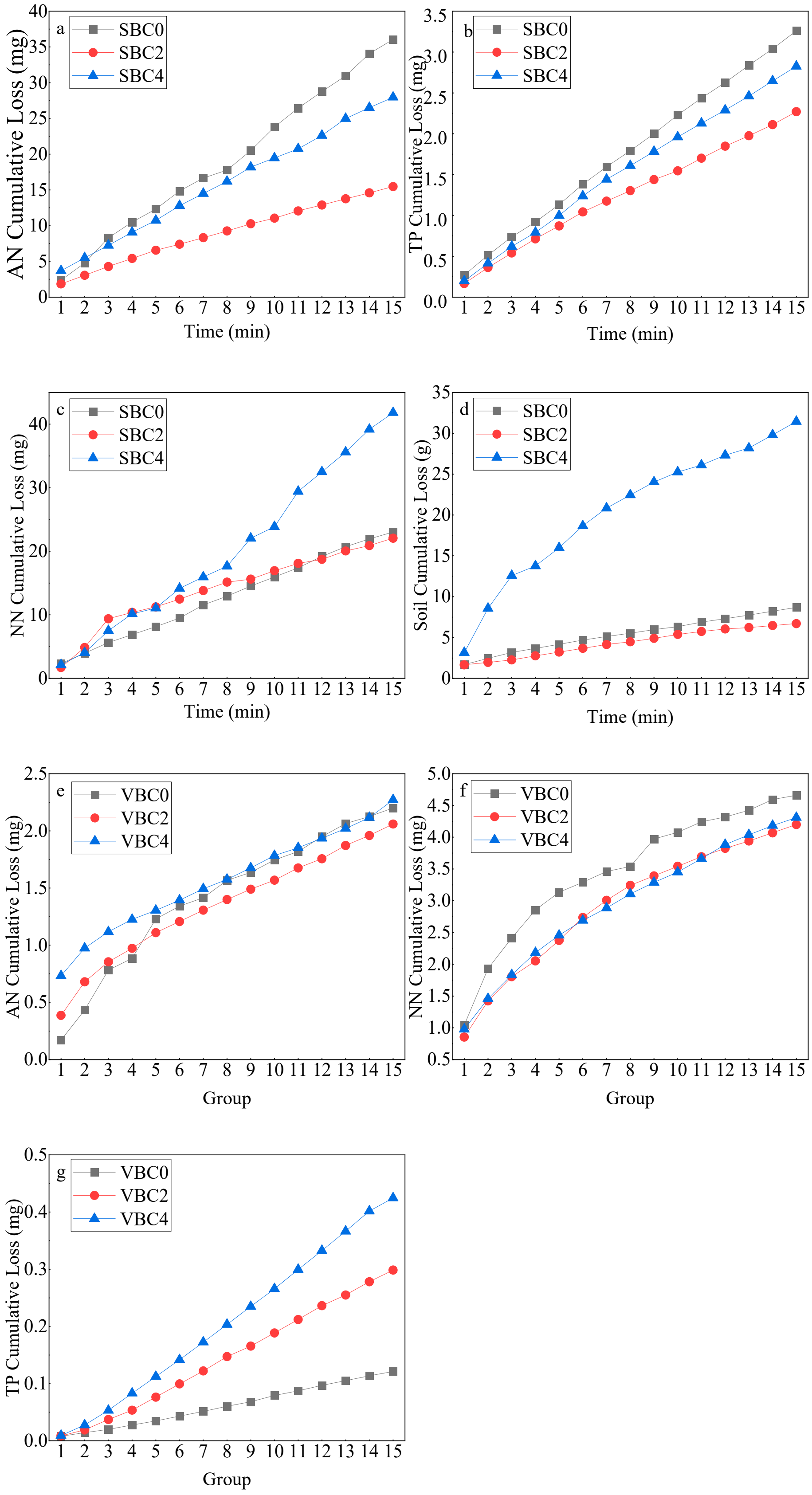


Figure 5. Cumulative loss of AN, NN, TP (**a**–**c**), and soil particles (**d**) from aqueous solution in slope experiment; cumulative loss of AN, NN, and TP (**e**–**g**) from aqueous solution in soil leaching experiment.

Table 4. Significance analysis of cumulative loss in slope simulation experiment and leaching experiment.

	SBC0	SBC2	SBC4	VBC0	VBC2	VBC4
AN/mg	36.04 ± 0.18 a	15.47 ± 0.012 b	27.96 ± 0.134 c	2.1 ± 0.01 a	2.06 ± 0.03 b	2.27 ± 0.01 c
NN/mg	23.04 ± 0.27 a	22.06 ± 1.655 a	41.81 ± 0.82 b	4.66 ± 0.032 a	4.2 ± 0.028 b	4.31 ± 0.03 c
TP/mg	3.26 ± 0.06 a	2.27 ± 0.56 b	2.83 ± 0.031 c	0.121 ± 0.002 a	0.299 ± 0.011 b	0.425 ± 0.001 c
Soil Loss/g	8.69 ± 0.17 a	6.71 ± 0.16 b	31.45 ± 0.32 c			

Lowercase letters after each value within the same line indicate a significant difference ($p < 0.05$, n = 3).

According to the data presented in Figure 4b, the NN content reached its highest point in the first minute for SBC0 (2.33 mg), the third minute for SBC2 (4.52 mg), and the thirteenth minute for SBC4 (5.54 mg). The cumulative loss of NN in SBC0, SBC2, and SBC4 was 23.04 mg, 22.06 mg, and 41.81 mg, respectively, during the 15 min runoff period (Figure 5c). The addition of 2% biochar resulted in a 4.25% reduction in NN loss, while the inclusion of 4% biochar led to an 81.47% increase in NN runoff loss compared to the control group without biochar treatment.

Figure 4c shows that the highest TP content was observed in the first minute for SBC0 (0.27 mg), the second minute for SBC2 (0.20 mg), and the sixth minute for SBC4 (0.24 mg). According to the data presented in Figure 5b, the cumulative TP loss in SBC0, SBC2, and SBC4 was 3.26 mg, 2.27 mg, and 2.82 mg, respectively, during the 15 min runoff period. The inclusion of 2% biochar resulted in a 30.37% reduction in TP loss, while the addition of 4% biochar only led to a 13.50% reduction compared to the control group. As shown in Table 4, the addition of biochar can significantly reduce the cumulative runoff loss of TP. Therefore, the addition of 2% biochar was more effective in inhibiting AN, NN and TP runoff loss than the addition of 4% biochar.

3.3. Leaching Loss of AN, NN, and TP

The time required for the leaching tests varied under the different treatments, with VBC0, VBC2, and VBC4 taking 176.6 min, 295.8 min, and 568 min, respectively. After adding biochar, the infiltration rate of the water was greatly slowed, and the more biochar that was added, the slower the rate. Based on the data presented in Figure 4e, VBC0, VBC2, and VBC4 had the highest concentrations of AN in the third, first, and first groups, respectively, with values of 0.35 mg, 0.39 mg, and 0.73 mg. It is worth noting that there was a consistent decrease in the AN leaching loss over time. Within the 15 groups, the cumulative AN loss in VBC0, VBC2, and VBC4 was 2.20 mg, 2.06 mg, and 2.27 mg, respectively (Figure 5e). Compared to VBC0, the cumulative AN loss decreased by 6.4% in VBC2, while it increased by 3.2% in VBC4. Adding 2% biochar can significantly reduce the leaching loss of AN (Table 4). These results demonstrate that the addition of biochar at an optimal concentration can effectively limit the leaching of AN from the soil, whereas excessive biochar concentration could exacerbate leaching.

Figure 4f shows a decreasing trend in the loss of nitrate nitrogen (NN) over time for each treatment. The highest nitrate contents were 1.04 mg in the first group, 0.86 mg in the second group, and 0.98 mg in the third group for VBC0, VBC2, and VBC4, respectively. It is worth noting that VBC0 had the highest cumulative NN loss of 4.66 mg, while VBC2 had the lowest NN loss at only 4.20 mg (Figure 5f). Compared to VBC0, the NN loss decreased by 7.51% in VBC4 (4.31 mg) and by 9.87% in VBC2. Adding biochar significantly reduced the leaching loss of NN (Table 4).

The highest total phosphorus contents in VBC0, VBC2, and VBC4, was 10.87 μg in the 10th group, 24.23 μg in the 12th group, and 35.12 μg in the 14th group, respectively. Figure 4g shows that the loss of TP in each treatment increased over time. Notably, VBC4 had the highest accumulative TP leaching loss, reaching 0.43 mg, while VBC2 recorded an accumulative loss of 0.30 mg (Figure 5g). In contrast, VBC0 had the lowest TP loss, reaching only 0.12 mg. The results show that the TP loss in VBC4 increased by 258.33% compared to VBC0, and in VBC2, it increased by 150.00%. These findings suggest that the addition of biochar may increase the risk of TP leaching loss.

3.4. Soil Runoff Loss and Soil Particle Sizes

Based on the data presented in Figure 4d, both SBC0 and SBC2 had the highest rate of solid loss in the first minute, while SBC4 reached its peak in the second minute. The rate of solid loss in all three groups gradually decreased over time. SBC4 had the highest accumulation of solid loss, reaching 31.45 g, which was a significant increase compared to that of SBC0 at 8.69 g (Figure 5d). In contrast, SBC2 exhibited the lowest amount of solid loss, measuring only 6.71 g, which represents a 22.78% reduction compared to SBC0.

Figure 6 shows that the introduction of biochar to the soil had opposite effects on the runoff loss of soil particles depending on their size. The runoff loss increased for soil particles around 2–20 µm, while it decreased for the soil particles around 20–200 µm. These findings suggest that the addition of biochar resulted in a reduction in the loss of larger soil particles.

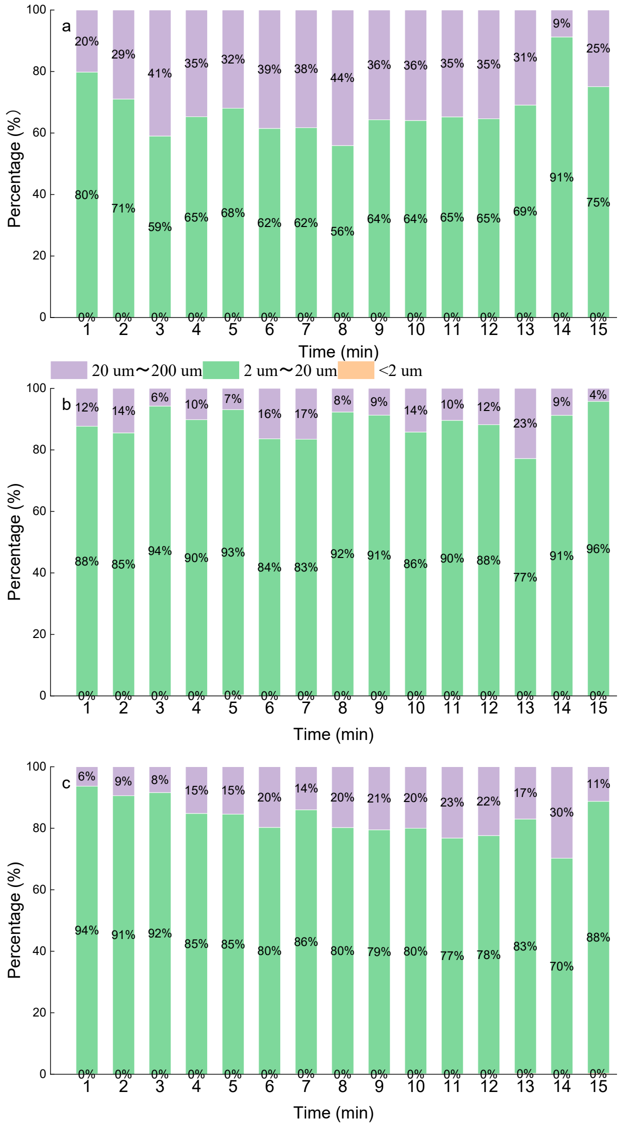


Figure 6. Soil particle size analysis of SBC0, SBC2, and SBC4 (**a**–**c**).

4. Discussion

4.1. Effects of Corn Straw Biochar on Nutrient and Soil Particles Adsorption in Slope Experiments

Over a period of 15 min, the concentration of AN in the solution decreased. The application of biochar enhanced the retention of NH_4^+-N [33]. Biochar has been shown to significantly increase soil CEC in sandy-textured soils [34], allowing it to adsorb and retain NH_4^+-N [35]. The adsorption capacity of biochar for NH_4^+-N is primarily due to its large number of acidic functional groups [35]. These groups have a negative charge and attract NH_4^+ through electrostatic forces [36]. Additionally, the presence of -OH in corn straw biochar can enhance the retention of NH_4^+-N. Cation exchange is also a contributing factor [37]. However, the addition rate of 4% was less effective in controlling the loss of NH_4^+-N compared to 2%. This may be due to the fact that biochar itself is rich in nitrogen and its addition introduces NH_4^+-N into the soil. Overall, the addition of biochar significantly reduced the AN loss. The inclusion of 2% biochar exhibited superior inhibitory effects on AN loss compared to 4% biochar, showcasing its potential in reducing AN loss in sloped areas subjected to rainfall.

This study found that the addition of 2% biochar reduced the NO_3^- -N loss by 4.25%, while the addition of 4% biochar increased the NO_3^- -N loss by 81.47%. It is important to use an appropriate biochar addition rate [38]. Biochar has several benefits, including the ability to adsorb nitrifier inhibitors from the soil, carry more negative surface charges than positive surface charges [36], enhance microbial biomass [37], and adsorb phenolics [39], which stimulate nitrification. However, it should be noted that biochar can still sorb nitrate through bridge bonding, as demonstrated by Mukherjee et al. (2011) [40]. Additionally, the use of soil with a low fertility and the corn straw biochar produced at 500 °C in this experiment may result in increased NO_3^- -N runoff loss, as reported by Kanthle et al. (2016) [41] and Yao et al. (2012) [42]. Another crucial factor affecting NO_3^- -N runoff loss is the pH value, which has been found to have a positive correlation with nitrate concentration [23]. The addition of biochar to the soil significantly increases the pH, as reported by Chen et al. (2021) [37]. This phenomenon also weakens the inhibitory effect of biochar on NO_3^--N loss as the amount of biochar added increases.

Compared to SBC0, SBC2 showed a 30.37% decrease in TP runoff loss, which was superior to that of SBC4. The addition of biochar significantly increased the soil pH value. When the pH value exceeded 7, phosphorus could precipitate with Ca^{2+} and be adsorbed on the surface of Fe^{3+} and Al^{3+} [14]. However, the increase in OH^- concentration resulted in competition between OH^- ions and phosphate, leading to a decrease in P adsorption [43]. In this study, it was found that the addition of biochar resulted in a decrease in the adsorption of phosphorus, leading to its desorption [44]. However, it should be noted that phosphorus present in the soil can migrate to deeper layers [4], resulting in a decrease in the runoff loss of total phosphorus after biochar addition.

Compared to SBC0, the addition of 2% biochar reduced the soil loss, thereby preserving soil and water. However, the addition of 4% biochar led to an increase in soil loss. This phenomenon could be attributed to the soil characteristics [21] and biochar addition rates. Wu et al. (2016) [45] found that only the addition of 3% biochar reduced the soil runoff loss, while the addition of 5% and 7% biochar increased soil erosion on the slope. The addition of corn straw biochar to soil can increase soil porosity, thereby reducing the soil bulk density [13,46]. However, excessive addition of biochar may result in excessively loose surface soil, leading to rapid soil loss when exposed to deionized water during the 15 min observation period. The effectiveness of 2% biochar addition in mitigating solid loss can be attributed to the adsorption capacity of biochar. Biochar forms organo-mineral complexes with soil minerals, as shown a study by Naggar et al. (2019a) [47], thereby mitigating their runoff loss. Further studies are needed to investigate the adsorption of soil particles by biochar.

4.2. Effects of Nutrient Adsorption by Corn Straw Biochar in Column Leaching Experiments

The accumulative AN leaching loss of VBC2 was significantly reduced by 6.4% compared to VBC0. However, the addition of 4% biochar increased the AN loss by 3.2%. This phenomenon could be attributed to the fact that biochar promotes the conversion of NN to AN [48]. The process of ammonification in soil is complex, as it is correlated with soil pH, WHC, and microorganism activities. Among these factors, soil microorganisms play a leading role [34]. Additionally, the AN leaching loss was mitigated by the biochar addition; this was attributed to the competing cations [9]. The presence of competing cations can hinder the ion exchange process. Additionally, the effectiveness of biochar in reducing the AN leaching loss varies depends on the rate that the biochar is added. Zhang et al. (2022) [49] found that adding 2–4% reed biochar produced positive results in mitigating AN loss. However, in our specific study, the addition of 4% corn straw biochar was not effective.

At the beginning of the soil leaching experiment, many NO_3^--N ions were carried away by the deionized water, which caused a lot of NN leaching losses. However, the NO_3^--N leaching losses were significantly affected by time [50], and a decreasing trend was observed in the 15 groups as the biochar adsorbed these ions [51] and nitrification was limited [52]. NO_3^--N adsorption was possible through the following mechanisms: (1) direct adsorption; (2) unconventional H-bonding between NO_3^- and the biochar surface [36]; (3) bridge bonding with divalent cations [53]; and (4) the ability of the functional groups to enhance the adsorption of nitrogen through specific interactions between electron donors and acceptors [54]. Another factor influencing NO_3^- -N adsorption was the pH value. The addition of biochar increased the soil's pH value, and the pH of the soil increased as the proportion of biochar applied increased. The effect of biochar on reducing N leaching was weakened at application rates of 2% and 4% [38]. Furthermore, bacteria are likely to increase with increasing pH, while fungi may reduce their growth at higher pH values ($pH > 7$) [39].

P is present in maize straw biochar. Therefore, the addition of biochar can increase the P content in the soil [54]. Compared with VBC0, the TP accumulative leaching loss increased by 146.05% (VBC2) and 249.94% (VBC4) in the soil column leaching experiment. Due to the negatively charged surface of biochar, it is difficult for it to adsorb phosphate ions [30]. Biochar can even release phosphate [42,55], and the addition of biochar can reduce soil P fixation [10,45], increase the available P content [5], and promote leaching losses of soluble phosphorus [33,56,57]. In our study, the incorporation of biochar contributed to an increase in soil phosphate leaching, with the magnitude of leaching being proportional to the amount of biochar added. In addition, the incorporation of biochar has the potential to alter soil pH value. Elevated pH levels can reduce the adsorption capacity of phosphates, making them more soluble and susceptible to leaching into the soil solution. Over time, the leaching loss of TP showed an increasing trend as the biochar was able to reach its maximum adsorption capacity [58].

The regulation of nutrient losses in the slope experiment and the soil leaching experiment was different, which may be related to the duration of the experiment and the soil water content. The pH and soil water content were also affected by the biochar addition. It is crucial to acknowledge that the regulation of nutrient runoff and leaching losses may vary depending on some important factors such as the agro-types, biochar species, and application rates, as well as time.

4.3. Resistance Control Mechanism Based on SEM and FT-IR Analyses

The maize straw biochar was characterized before and after adsorption to analyze any changes in its shape and functional groups (Figure 3). Notably, Gillingham et al. (2022) [59] observed that biochar obtained from crop sources showed improved surface functionality. The SEM results confirmed the presence of abundant pores and the excellent adsorption performance of the maize straw biochar. Biochar extracted from soil adheres to many tiny particles, which has a certain effect on preventing nutrient loss. Feng et al. (2022) [60] discovered that -OH groups on biochar can adsorb NH_4^+ on the biochar surface through electrostatic attraction, thereby playing a role in the immobilization of soil AN. The disappearance of the absorption peak associated with the benzene ring (Figure 6) could be interpreted as the adsorption of nutrients or soil particles. The peak at around 1600 cm^{-1} corresponds to the C-C bond and bending vibrations of the -OH group associated with metal hydroxides and the interlayer water [61]. As shown in Figure 3, the biochar initially had a peak around 3200 cm^{-1}, which can be attributed to the absorption of -OH groups, indicating the presence of primary alcohols, and a peak around 1600 cm^{-1}, which is characteristic of aromatic compounds, indicating the presence of benzene rings. The peak at 1411 cm^{-1} corresponds to the bending vibration of C-H in alkane, while the peak at 1050 cm^{-1} indicates the stretching vibration of C-O. The peaks appearing between 750 and 880 cm^{-1} were assigned to the out-of-plane bending vibrations of the benzene ring. Thus, before adsorption, the biochar contained benzene rings, primary alcohols, and alkane groups. After adsorption, the peak at around 3600 cm^{-1} is characteristic of the absorption of O-H in alcohols, indicating the presence of -OH in the biochar. An absorption peak at 1010 cm^{-1} represents C-C bonds and another at 1417 cm^{-1} indicates the presence of alkane groups. The peaks at about 690 cm^{-1} and 1630 cm^{-1} correspond to the out-of-plane bending vibrations of the olefin, indicating the presence of unsaturated double bonds on the biochar. In addition, the peak at 786 cm^{-1} represents the C-H bending vibrations of olefin. Thus, olefin groups were present on the biochar after adsorption. The FT-IR results indicated the presence of alkene and hydroxyl groups in the biochar, and the presence of oxygen-containing functional groups makes the activated carbon hydrophilic, thereby facilitating adsorption reactions.

5. Conclusions

In this research, the inhibitory effects of biochar on AN, NN, TP, and soil losses were investigated through slope and soil column leaching experiments. In addition, the biochar was characterized to gain an insight into its adsorption mechanism. In the slope experiments, the 2% biochar addition resulted in reduced losses of AN, NN, TP, and soil particles due to runoff compared to the 4% addition. This reduction was primarily attributed to a reduction in the loss of soil particles with diameters greater than 20 microns. Similarly, the 2% biochar addition was effective in reducing the leaching losses of AN and NN. However, in the soil leaching process, the total phosphorus losses were potentially enhanced by the 2% biochar addition. It is important to note that leaching losses of TP are influenced by several factors that need to be further investigated in future research. The honeycomb structure of maize straw biochar produced by high-temperature anaerobic pyrolysis is a factor due to its large specific surface area. In addition, the presence of hydroxyl groups on the biochar surface made it hydrophilic, which increased its adsorption capacity. The disappearance of the absorption peak related to the benzene ring can be attributed to the occurrence of adsorption reactions. Furthermore, adding 2% biochar is more economical. In summary, the optimal concentration for this experiment was 2% biochar. However, this study only focused on simulating the nitrogen and phosphorus inhibition effect of a single biochar over a short time scale, and the results may have limitations in terms of clustering and concentrated flow areas. In the future, we will continue to pay attention to the control process and related mechanisms of different types of biochar under natural rainfall conditions, and we will also seek a more comprehensive experimental plan.

Author Contributions: L.X.: formal analysis, software, writing—original draft, conceptualization, methodology. X.N.: data curation, funding acquisition, supervision, writing—review and editing. X.Y.: resources, project administration. Z.D.: investigation, data curation. A.L.: funding acquisition, supervision. Y.M.: funding acquisition. P.G.: funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China [grant number 41703099], the Major Research Plan of the Shandong Natural Science Foundation [grant number ZR2020ZD19], and the Natural Science Foundation of Shandong Province, China [grant numbers ZR2020MD108, ZR2020ME251].

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Thank you to the laboratory staff for their efforts in the experiment.

Conflicts of 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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