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Research Article

Evaluation of Agricultural Soils Amended with Crop Straw and Straw Biochar on Reduction of Nitrogen and Phosphorus Runoff and Leaching Losses

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Abstract

Nitrogen (N) and phosphorus (P) losses throughout agricultural soils runoff and leaching can contribute to agricultural non-point source pollution. Here, we conducted an evaluation of long-term effects of mineral fertilizer (NPK), crop straw combined with mineral fertilizer (CSNPK), crop straw biochar combined with mineral fertilizer (BSNPK), and the control with no fertilizer (CK) on runoff and leaching losses of N and P forms in the intensive agricultural cropland. Following that, nitrogen and phosphorus runoff and leaching losses were measured using the free-drain field lysimeter method overs a two years experiment. The results indicated that, the nitrogen forms runoff losses of nitrate N, dissolved organic N and particulate N, accounted by 12.0-64.0%, of the total N runoff losses, while the phosphorus forms runoff losses of particulate P accounted about 98.0% of the total P runoff losses. Similarly, nitrate N, dissolved organic N and particulate N leaching losses, accounted for 25-61% of total N leaching losses, whereas, particulate leaching loss accounted 87% of the total P leaching losses. The total N and P losses fluxes strongly correlated with runoff and leaching discharges, while the relationships between total P losses fluxes and leaching discharges was described by a significant exponential function. The study shows that the combination of crop straw of either straw of biochar with mineral fertilizer could significantly reduce N and P runoff and leaching losses.

Keywords

Agricultural Soils, Nutrient Losses, Hydrological Losses, Non-Point Source Pollution

1. Introduction

In sub-tropical regions, agriculture faces challenges related to the management of essential nutrients such as nitrogen (N) and phosphorus (P), mainly due to the low capacity of soils to retain these elements [1, 2]. Likewise, soils are often depleted by intensive farming practices and inadequate management, leading to declining fertility and insufficient yields [3, 4]. Losses of N and P not only hinder agricultural productivity but also pose significant environmental risks, including water contamination and eutrophication [5, 6].

To address these challenges, the application of biochar and crop residues is being explored as an innovative strategy to enhance nutrient retention and soil fertility [7, 8]. Biochar,

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produced through the pyrolysis of biomass in a controlled environment, has a microporous structure capable of retaining large amounts of nutrients and water, thereby significantly improving soil structure [9, 10]. This material is recognized for its ability to increase N retention in soils, reducing nitrous oxide (N_2O) emissions and nitrate leaching [11]. Crop residues, on the other hand, contribute to increasing organic matter and support microbial activity, which is essential for nutrient cycling [12, 13].

The combined interest in biochar and crop residues stems from their synergistic effects. According to Nguyen et al. [5], the addition of crop residues enhances the effectiveness of biochar by increasing microbial diversity and nutrient availability. Moreover, a study by Spokas et al. [14] observed that the combination of these two amendments reduced N and P losses, enabling more sustainable nutrient retention in soils. This finding is further supported by research from van Zwieten et al. [15], which showed increased plant growth in soils amended with biochar and organic matter, particularly in tropical soils.

Purple soils, also classified as Eutric Regosols according to the FAO soil taxonomy, are considered acidic and prone to N and P losses via hydrological pathways in the Sichuan region. This region also suffers from severe soil erosion and nutrient leaching, making these amendments a potentially effective and sustainable solution [10, 16]. Furthermore, the application of biochar could contribute to soil carbon sequestration, potentially playing a role in reducing greenhouse gas emissions [3, 17]. By integrating biochar and crop residues into agricultural practices, farmers in this region could not only enhance crop productivity but also promote sustainable soil management practices, thereby reducing the environmental footprint of their agricultural activities [18, 19].

This research aims to evaluate the impact of these two types of amendments on nutrient retention and soil structure, with a focus on their effects in reducing N and P losses under the pedoclimatic conditions of Sichuan basin. By relying on experimental results and comparing the effects of the amendments, this study will contribute to the current understanding of sustainable agricultural practices in tropical regions [1, 17]. The findings will provide insights into how these interventions can improve soil productivity while offering an environmentally friendly approach to sustainable agriculture [6, 13].

2. Materials and Methods

2.1. Study Area

The study site is located in the purple soil region of Sichuan Province, China. This type of soil, characterized by low organic matter content, poor water retention capacity, and weak structure, is common in the hilly areas of this region. The experiment was conducted on sloping land, where lysimeter plots were established to collect data on runoff namely overland flow and leaching called interflow within the winter wheat–summer maize crop rotation system. Figure 2 illustrates the study area, adapted from the map by Bah et al. [20].

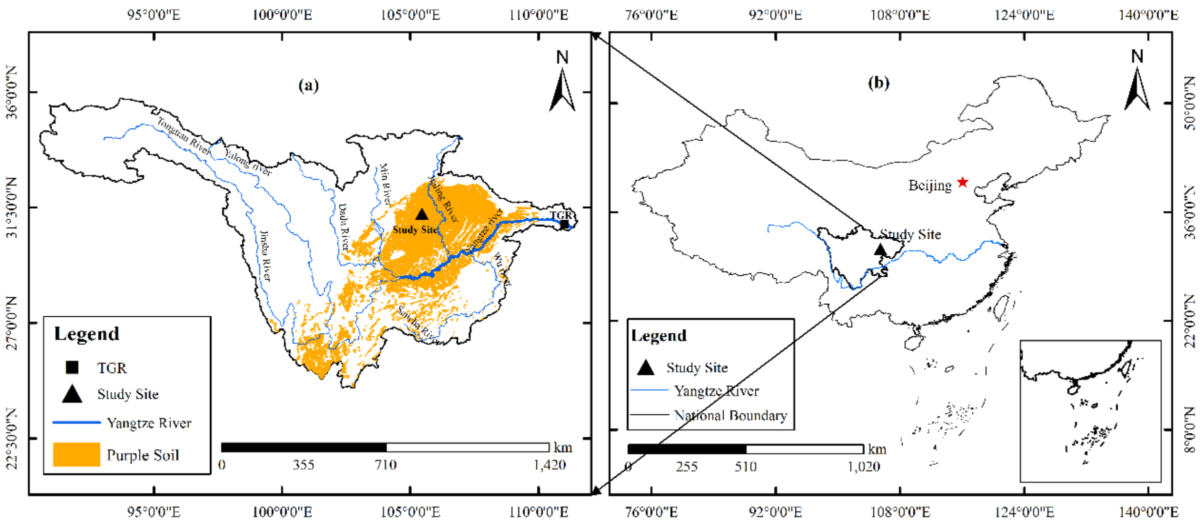

Figure 1. *Study area showing the distribution of purple soils in the upper reaches of the Yangtze River, Sichuan Province.*

2.2. Data Collection Method

Nitrogen and phosphorus losses in the field were monitored using a large-scale free-drainage lysimeter plot. The free-drainage lysimeter plots (size: 8 x 4 m^2; slope: 6.5°), constructed in 2001, allowed for the measurement of both surface runoff (overland flow) and leachate (inteflow) water [21] as shown in (Figure 2). The experiment was conducted using a randomized block design with four (4) treatments and three replications within a winter wheat–summer maize crop rotation system. The treatments included: mineral fertilizer

(NPK), crop straw combined with mineral fertilizer (CSNPK), crop straw biochar combined with mineral fertilizer (BSNPK), and a control without fertilizer (CK).

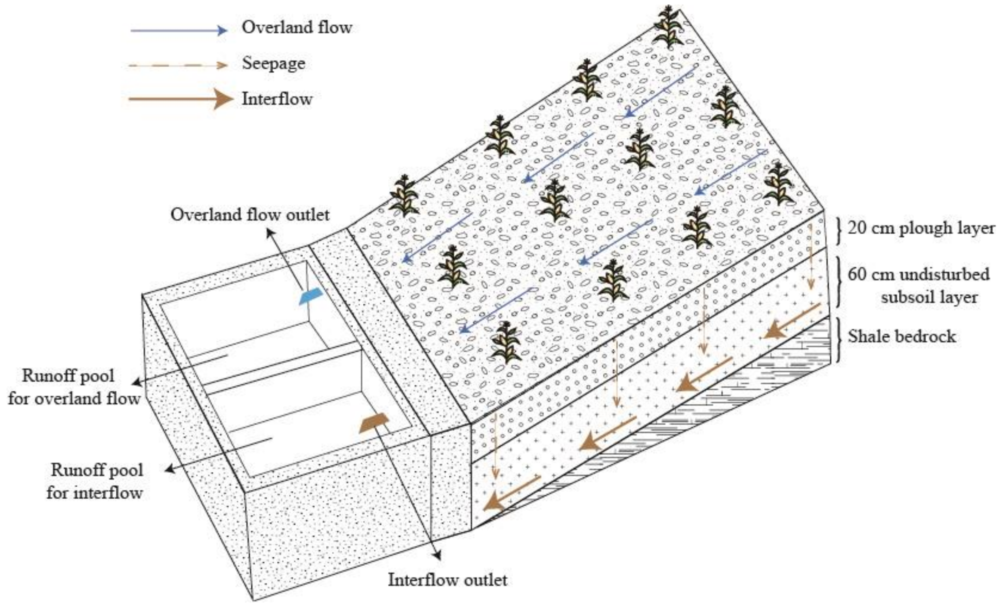

Figure 2. *Conceptual model of the structure of the runoff plot on the purple soil's sloping upland from Jiang et al. [22].*

2.3. Methods for Measuring Runoff and Leachate

To measure runoff and leachate, each free-drainage lysimeter plot was hydrologically isolated using cement partitions. These partitions were embedded at least 60 cm into the bedrock to prevent unexpected seepage into other plots [21]. The experimental free-drainage lysimeter was equipped with a convergence trough at the topsoil and bedrock surface levels to quantify runoff (overland flow) and leaching (interflow) after each rainfall event. Separate ponds were constructed below each convergence trough to collect both runoff and leachate water [23].

Monthly precipitation and temperature data during the wheat and maize growing periods were collected from a nearby weather station (100 m from the experimental site), and the results are presented in Figure 2. Before sample collection, water levels in each pond were measured at four different points. Runoff and leachate water were collected using 500 ml pre-cleaned polyethylene bottles. Water samples were taken from different ponds after each rain event, once water flow had stopped. Runoff samples were thoroughly mixed before sampling to ensure homogeneity, and samples were left for 3 days to allow sedimentation.

2.4. Analysis of Nitrogen and Phosphorus in Runoff and Leachates

After field sampling, runoff and leachate water were analyzed for nitrogen and phosphorus compounds. Except for the determination of total nitrogen (TN) and total phosphorus (TP), water samples were filtered using Whatman No.5 filter paper. The concentrations of dissolved total nitrogen (TDN), NH_4^+-N, NO_3^--N, dissolved total phosphorus (TDP), and phosphate (PO_4^{3-}-P) in the filtrates were analyzed using a continuous flow autoanalyzer (model AA3, Bran + Luebbe, Norderstedt, Germany). Additionally, dissolved organic nitrogen (DON) was calculated as TDN minus the sum of NH_4^+-N and NO_3^--N. Particulate N and P, referred to as PN and PP, were calculated as TN and TP minus TDN and TDP, respectively, following Gao et al. [24]. (2014). Loss fluxes of N and P, as well as cumulative loss fluxes from runoff and leaching, were calculated by multiplying the respective concentrations of N and P by the corresponding number of runoff or leaching events throughout the year.

2.5. Data Analysis Method

Statistical analysis was conducted to evaluate the effects of treatments on nutrient (N and P) losses through runoff and leaching, as well as on nutrient and water retention in agricultural soils. The concentrations of N and P measured in runoff and leachate samples were multiplied by the volumes of water collected for each rainfall or irrigation event, allowing for the calculation of total N and P loss fluxes for each treatment. Data were aggregated by year and by treatment (CK, NPK, CSNPK, BSNPK) to facilitate comparisons between treatments and across years.

A one-way analysis of variance (ANOVA) was performed to assess the impact of treatments on variables such as N and P losses through runoff and leaching, and biomass and grain yields. The ANOVA determined whether the differences observed between treatments were statistically significant, using a significance threshold of 5% ($p < 0.05$). For variables showing significant differences in the ANOVA, a Tukey post-hoc test was applied to identify specific differences between treatment pairs. In the result graphs, distinct letters above the bars indicate statistical differences, making it easier to visually interpret variations between treatments.

3. Results

3.1. Impact of Climatic Conditions on Nutrient Retention

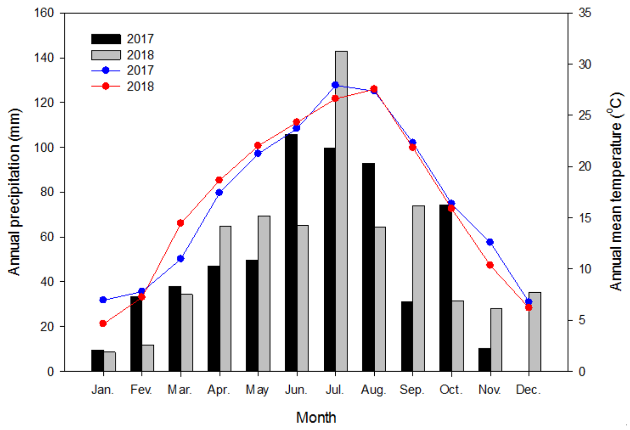

Figure 3. *Annual precipitation and average temperature during the two experimental years (2017 and 2018).*

Figure 3 illustrates how variations in precipitation and temperature between the two experimental years directly influence the dynamics of runoff and interflow. High rainfall, combined with higher summer temperatures, intensifies runoff and increases nutrient losses, whereas low rainfall tends to limit these losses. These climatic conditions are therefore crucial for determining the effectiveness of nutrient retention.

3.2. Improvement in Biomass and Grain Yields

The results indicate that treatments incorporating organic amendments (CSNPK and BSNPK) produced significantly higher biomass yields compared to the control (CK) and mineral (NPK) treatments. This trend was observed for both years, although overall yields were higher in 2017 than in 2018. The CSNPK and BSNPK treatments enhanced water and nutrient retention in the soil, promoting crop growth, as evidenced by the increased biomass of wheat and maize. In contrast, the CK and NPK treatments exhibited lower yields, reflecting their reduced effectiveness in nutrient retention and soil property improvement (Figure 4).

Grain yields followed a similar trend to biomass yields, with superior performance observed for the CSNPK and BSNPK treatments. In both 2017 and 2018, these treatments produced the highest grain yields for wheat and maize, confirming the efficacy of adding biochar and crop residues in maximizing crop productivity. The CK treatment, however, remained the least effective, while the NPK treatment produced intermediate results. This yield disparity highlights the importance of organic amendments in soil management, especially under conditions requiring effective water and nutrient retention (Figure 5).

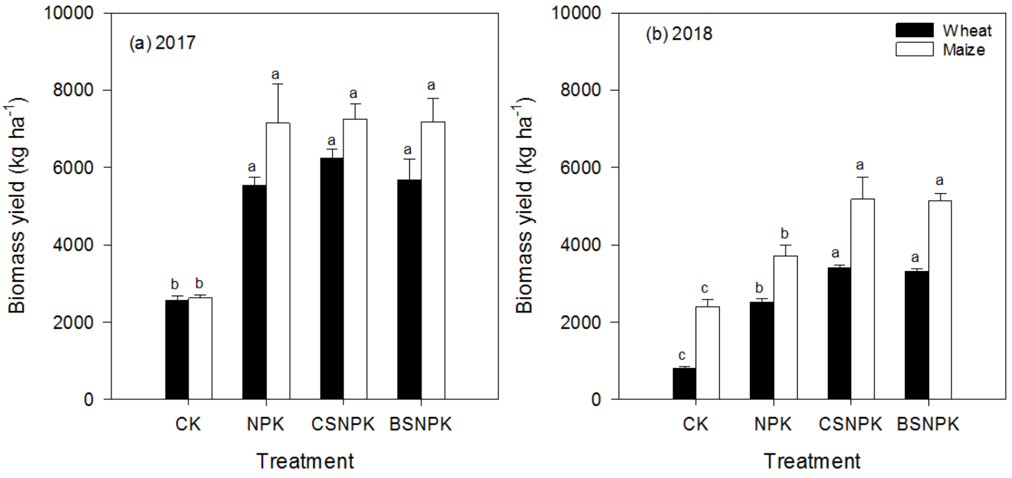

Figure 4. *Biomass yield of crops (wheat-maize) for each treatment.*

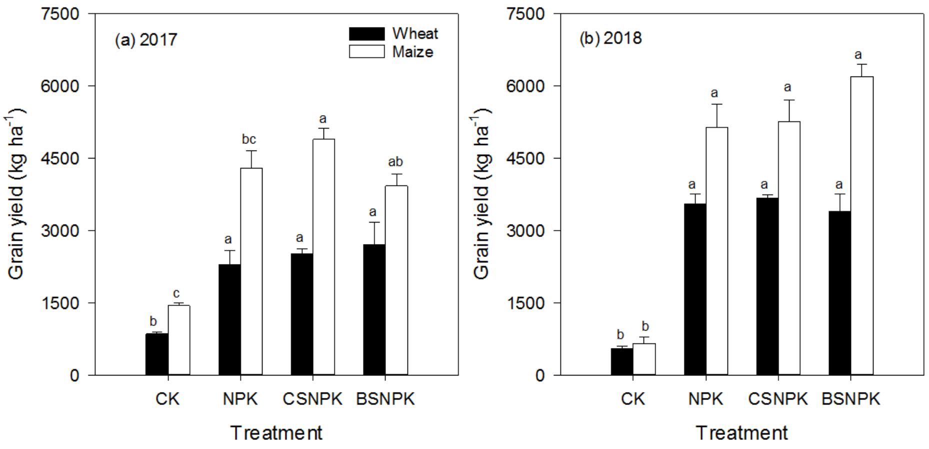

Figure 5. *Grain yield of crops (wheat-maize) for each treatment.*

3.3. Increased Nutrient Uptake by Plants

Figure 5 presents nitrogen uptake (in kg N ha^{-1}) for wheat and maize under four treatments (CK, NPK, CSNPK, BSNPK) during the years 2017 and 2018. This analysis highlights the influence of organic and mineral amendments on the nitrogen use efficiency of crops.

The CSNPK (crop residues + mineral fertilizers) and BSNPK (biochar + mineral fertilizers) treatments stand out with significantly higher nitrogen uptake for wheat and maize compared to the control (CK) and the NPK treatment. This trend is consistent across both years, confirming the positive impact of biochar and crop residues on nitrogen retention in the soil, making it more available to plants. This increased nitrogen uptake is critical for enhancing agricultural productivity and ensuring sustainable farming practices.

Nitrogen uptake was generally higher in 2017 than in 2018, though the trends for each treatment remained similar. This variation could be attributed to more favorable climatic conditions in 2017, such as an optimal distribution of rainfall and moderate temperatures, which likely improved nutrient uptake by crops. In contrast, less favorable conditions in 2018 may have negatively affected nitrogen use efficiency, reducing plant uptake.

The control treatment (CK), without any amendment, exhibited the lowest nitrogen uptake levels for both crops, as expected due to the lack of additional nutrients. The NPK treatment, while providing nutrients in mineral form, did not match the efficiency of the CSNPK and BSNPK treatments. This is likely because mineral fertilizers alone have a lower nitrogen retention capacity and are more prone to leaching without organic matter like biochar.

Distinct letters above the bars in Figure 5 indicate statistical differences between treatments. For instance, in 2017, wheat under the BSNPK treatment (letter "a") exhibited significantly higher nitrogen uptake than under the CK treatment (letter "c"), confirming that biochar addition enhances nitrogen availability. The statistical differences between treatments further reinforce the effectiveness of biochar and crop residues in improving nutrient uptake by plants.

The integration of biochar and crop residues into soils enhances nitrogen retention, limiting losses through leaching and making it more available to crops. Biochar, in particular, acts as an adsorbent for nitrogen ions, reducing leaching and increasing the availability of this nutrient throughout the growing season.

Nitrogen uptake was higher across all treatments in 2017 compared to 2018, likely due to the differing climatic conditions between the two years. Favorable weather conditions in 2017, including better-distributed rainfall and moderate temperatures, likely supported better nitrogen utilization.

The CK treatment consistently showed the lowest nitrogen uptake for wheat and maize, reflecting the absence of additional nutrients. While the NPK treatment provided direct nutrient availability, it was less effective than the CSNPK and BSNPK treatments in retaining and supplying nitrogen to plants. This emphasizes the importance of organic amendments, which enhance nutrient retention and reduce the risk of losses through leaching.

Statistical differences marked by distinct letters confirm the superiority of the BSNPK and CSNPK treatments in nitrogen uptake. For example, in 2017, wheat under the BSNPK treatment (letter "a") demonstrated significantly higher nitrogen uptake than wheat under CK (letter "c"), highlighting the substantial benefit of biochar addition. These findings support the hypothesis that biochar treatments promote more efficient nitrogen use by crops.

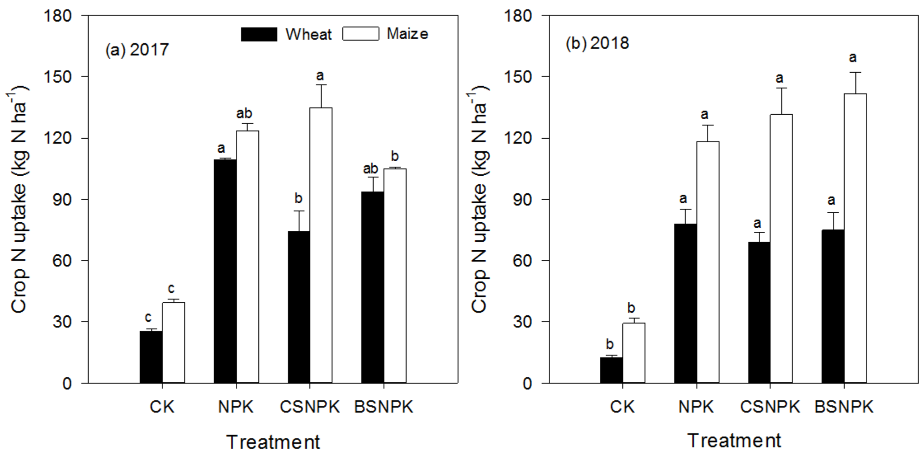

Figure 6. Nitrogen uptake by crops for each treatment.

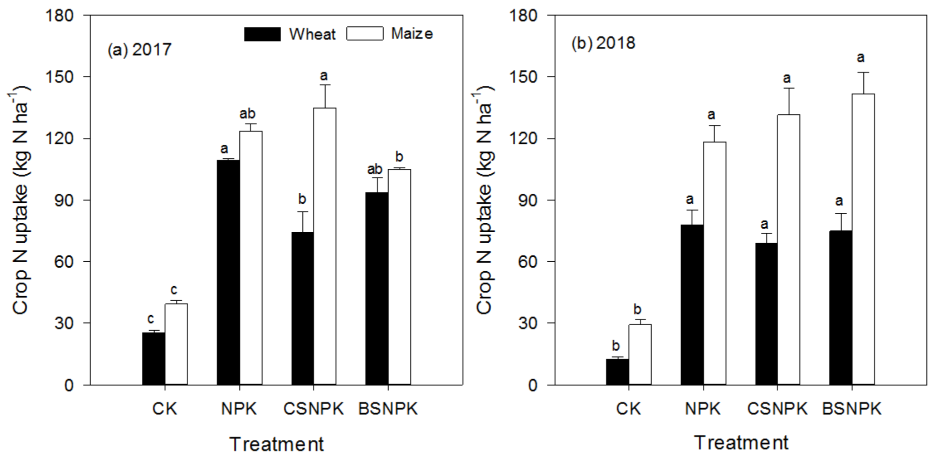

Figure 7. Phosphorus uptake by crops for each treatment.

3.4. Effect of Treatments on Overland Flow and Interflow Rates

Figure 7 shows water overland flow and interflow rates (in mm) under different treatments (CK, NPK, CSNPK, BSNPK) for the years 2017 and 2018. These results highlight the influence of organic and mineral amendments on water flow control, a crucial factor for reducing soil erosion and nutrient losses.

The treatments combining crop residues (CSNPK) and biochar (BSNPK) exhibit the lowest water flow rates, both for surface runoff and interflow, compared to the control (CK) and NPK treatments. This reduction in water flow is consistently observed across both years, suggesting that biochar and crop residues enhance the soil's water retention capacity, thereby mitigating risks of erosion and nutrient loss.

Biochar application improves soil structure by increasing porosity and water retention capacity. This not only reduces surface runoff but also interflow, thereby limiting the transport of particles and nutrients away from crop fields.

Water flow rates are slightly higher in 2018 than in 2017 for all treatments. This difference can be attributed to climatic variations, such as increased rainfall in 2018, which raises the likelihood of runoff and interflow. However, even under higher rainfall conditions, the CSNPK and BSNPK treatments maintain lower water flow rates than CK and NPK, underscoring their effectiveness in managing water flows in soil.

The control treatment (CK) shows the highest water flow rates, indicating a low water retention capacity in unamended soil. The NPK treatment, using only mineral fertilizers, exhibits similarly high-water flow rates, suggesting that mineral fertilizers alone are ineffective in improving soil structure and controlling water flows. These findings indicate that mineral fertilizers may be quickly leached or washed away, compromising their long-term effectiveness.

Statistical differences between treatments are represented by distinct letters above the bars. For example, in 2017, interflow rates for CK and NPK are statistically higher (letter "a") compared to CSNPK and BSNPK (letters "b" and "c"). This statistical differentiation confirms that the CSNPK and BSNPK treatments are significantly more effective in reducing water flow rates.

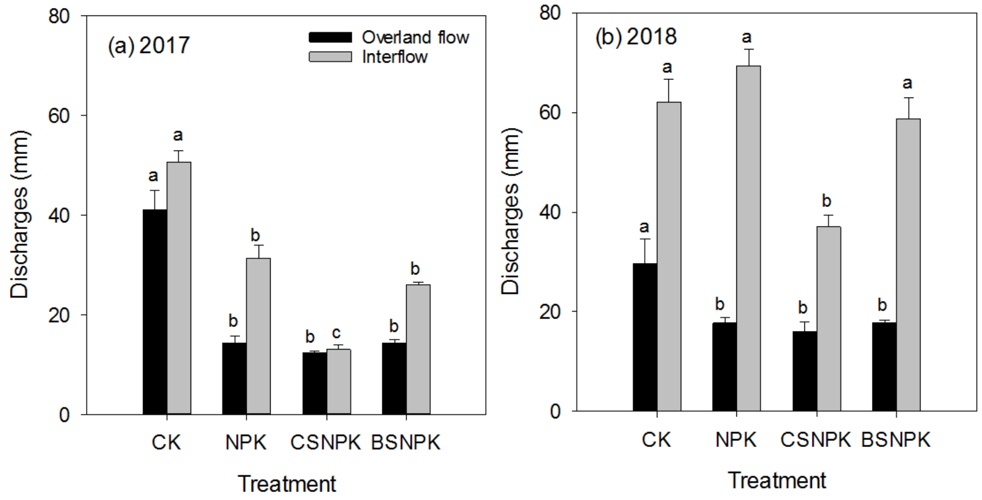

Figure 8. Water runoff and interflow rates under different treatments in 2017 and 2018.

3.5. Impact of Treatments on Reducing Nitrogen and Phosphorus Losses

Figure 9 illustrates nitrogen losses via surface runoff for various forms, including NH_4^+, NO_3^-, particulate nitrogen (PN), and dissolved organic nitrogen (DON) during 2017 and 2018. The CSNPK and BSNPK treatments exhibit significantly reduced losses for most forms, particularly nitrates (NO_3^-) and particulate nitrogen (PN), compared to CK and NPK treatments. These results suggest that biochar (BSNPK) and crop residues (CSNPK) improve the retention of mobile nitrogen forms, thereby limiting their displacement through surface runoff. Subfigures (c) and (d) display nitrogen losses via interflow for the same forms. Nitrogen losses through interflow are generally lower under the CSNPK and BSNPK treatments compared to CK and NPK, particularly for nitrates and particulate nitrogen. Enhanced nitrogen retention in soils treated with biochar and crop residues is essential to prevent leaching, especially in sloping soils or regions prone to high leaching rates. The results indicate that the use of biochar (BSNPK) and crop residues (CSNPK) effectively reduces nitrogen losses in the form of nitrates and particulate nitrogen, which could enhance soil fertility and reduce water pollution. Statistical differences among treatments, indicated by letters, confirm that losses are significantly lower for CSNPK and BSNPK treatments (Figure 8).

Subfigures (a) and (b) present phosphorus losses via surface runoff for forms such as orthophosphate (PO_4^{3-}), particulate phosphorus (PP), and dissolved organic phosphorus (DOP) in 2017 and 2018, respectively. The BSNPK treatment exhibits the lowest losses for particulate phosphorus (PP), the predominant form of phosphorus lost via runoff. CK and NPK treatments record the highest phosphorus losses, indicating limited efficiency in retaining phosphorus forms, particularly in unamended soils (CK). Subfigures (c) and (d) show phosphorus losses via interflow for the same forms. Particulate phosphorus (PP) losses via interflow are also significantly lower under CSNPK and BSNPK treatments compared to CK and NPK. The efficiency of these amendments in retaining phosphorus in the soil is crucial for reducing nutrient losses, particularly in agricultural systems where phosphorus is essential for plant growth. The results demonstrate that biochar (BSNPK) and crop residues (CSNPK) effectively reduce phosphorus losses, mainly in particulate form, through surface runoff and interflow. These treatments enhance nutrient retention, contributing to sustainable soil fertility and water quality protection (Figure 10).

Figures 9 and 10 demonstrate that the application of biochar and crop residues significantly reduces nitrogen and phosphorus losses, especially for their most mobile forms, by limiting their displacement through runoff and interflow. The CSNPK and BSNPK treatments show clear advantages in nutrient retention, improving soil fertility while minimizing the risk of pollution in surrounding water bodies. These findings support the adoption of organic amendments like biochar for more sustainable and environmentally friendly agricultural soil management.

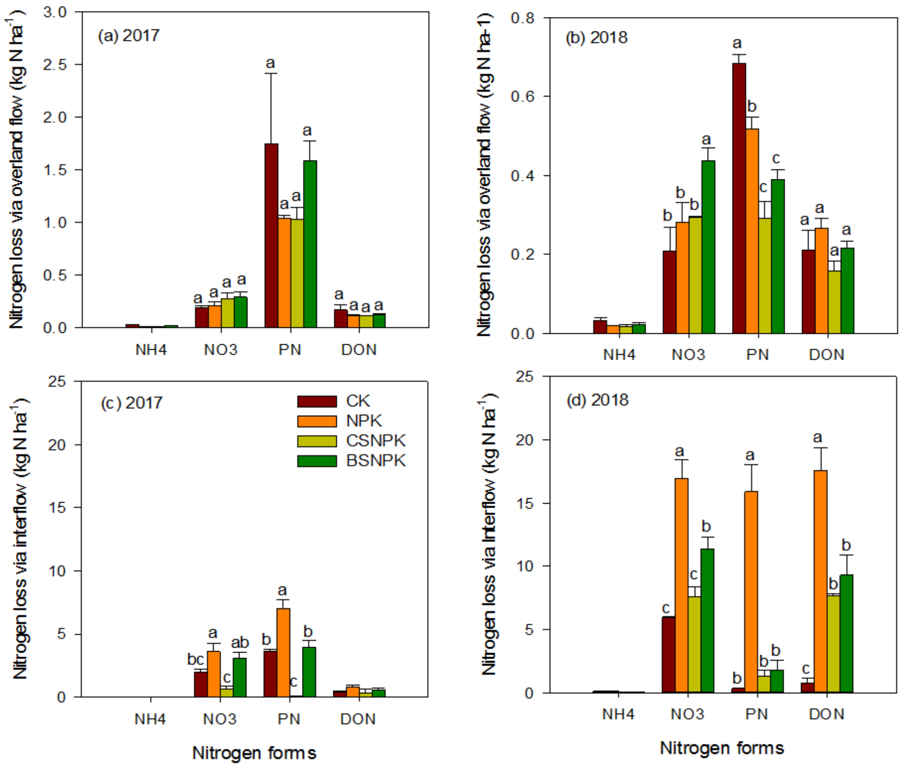

Figure 9. *Contributions of different nitrogen loss forms via overland flow and interflow for each treatment.*

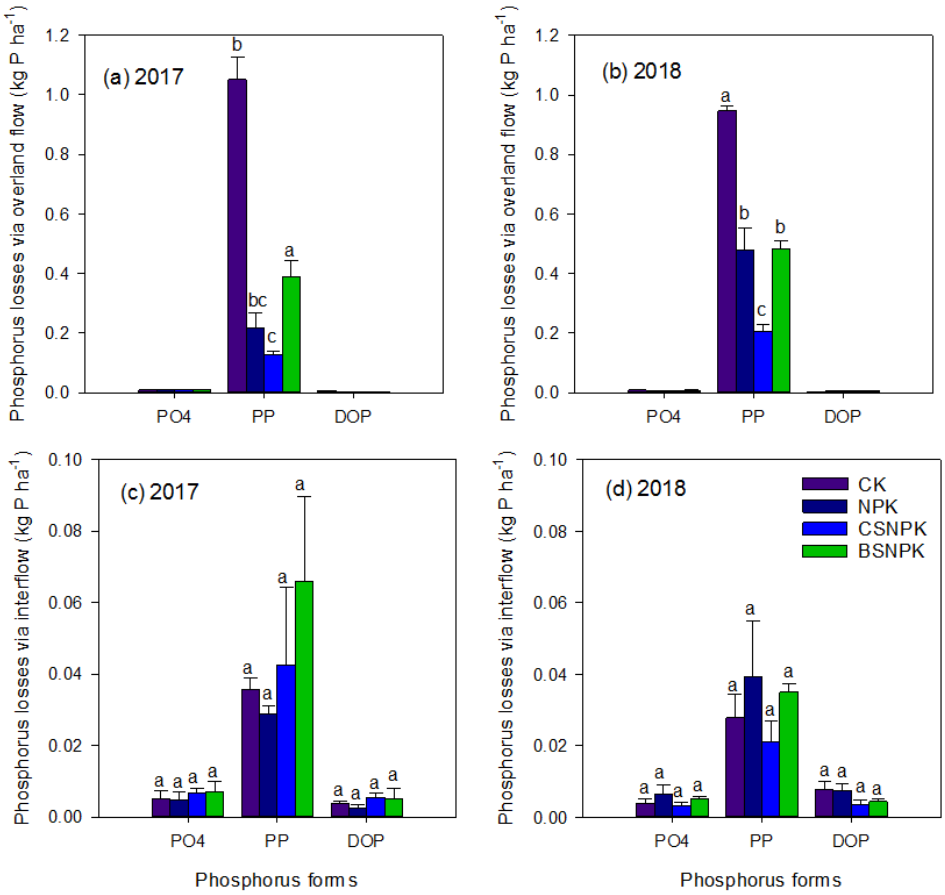

Figure 10. *Contributions of different phosphorus loss forms via overland flow and interflow for each treatment.*

4. Discussion

4.1. Impact of Climatic Conditions on Crop Yield and Nutrient Retention

The results of this study show that precipitation and temperature directly influence runoff and interflow dynamics, significantly affecting nutrient retention. High rainfall, combined with elevated temperatures, promotes runoff, leading to increased nutrient losses [25]. This phenomenon has been well-documented in similar environments where climate change exacerbates nutrient losses through extreme climatic events, such as heavy rainfall episodes and droughts [16, 26]. Conversely, lower rainfall reduces runoff and limits nutrient loss, potentially contributing to improved long-term soil fertility [27].

The findings indicate that treatments incorporating organic amendments, particularly biochar (BSNPK) and crop residues (CSNPK), result in significantly higher biomass and grain yields. These observations align with studies by Lehmann and Joseph [25], which demonstrated that biochar improves nutrient retention in soil, enhancing agricultural productivity. Xu et al. [28] further confirm that biochar and organic residues enhance water retention capacity and nutrient availability, creating favorable growth conditions for crops.

Nitrogen (N) and phosphorus (P) uptake were also enhanced in the CSNPK and BSNPK treatments. These results are consistent with studies by Jiang et al. [22], which showed that biochar addition improves nutrient availability to plants by reducing nutrient leaching. The increased nutrient uptake in biochar treatments can be attributed to improved ion retention in the soil, which minimizes losses through leaching [29, 30].

4.2. Effect of Treatments on Overland Flow and Interflow Rates

The significant reduction in water runoff and interflow rates observed in the CSNPK and BSNPK treatments has also been documented in other studies [16, 31]. (Novak et al., 2019; Jeffery et al., 2021). These studies suggest that biochar enhances soil structure, increasing its porosity and water retention capacity. Reduced water flow is crucial for minimizing soil erosion and nutrient loss, particularly in sloping soils where erosion risks are heightened [32].

Nitrogen and phosphorus losses, primarily in soluble forms (nitrates and orthophosphates), were significantly reduced in the BSNPK and CSNPK treatments. This supports findings by Xu et al. [28], who observed that biochar acts as an adsorbent for nutrient ions, reducing their mobility and runoff losses. Furthermore, Chen et al. [33] demonstrated that crop residues and biochar enhance nutrient retention in soils, mitigating the risk of surface water pollution, a critical concern for agricultural sustainability.

The analysis of nitrogen and phosphorus loss forms indicates that the CSNPK and BSNPK treatments better retain particulate nitrogen and phosphorus, which is essential for limiting eutrophication in water bodies. This retention is strengthened by the porous structure of biochar, which traps particles and reduces their transport from agricultural fields [30, 34]. By decreasing nutrient mobility, biochar contributes to sustainable soil fertility while preserving water quality.

5. Conclusion

This study highlights the beneficial impact of organic amendments, particularly biochar (BSNPK) and crop residues (CSNPK), on nutrient retention, reduction of losses via runoff and interflow, and the improvement of agricultural yields for wheat and maize. The results demonstrate that the integration of biochar and crop residues enables more effective retention of nitrogen and phosphorus in the soil, limiting their displacement and reducing the risks of leaching and pollution of surrounding water bodies.

Biomass and grain yields were higher in years with more favorable climatic conditions, but the CSNPK and BSNPK treatments showed relatively stable and high performance under both climatic contexts. This confirms their role in optimizing nutrient uptake, even in the face of variable climatic conditions. Moreover, the significant reductions in overland flow and interflow rates observed in plots treated with biochar and crop residues indicate improved soil structure, increased porosity, and enhanced water retention capacity. These combined effects contribute not only to better nutrient use but also to sustainable water management and reduced erosion both critical factors for sustainable agriculture.

The use of biochar and crop residues as agricultural amendments emerges as a promising strategy for improving soil fertility, reducing nutrient losses, and increasing yields while minimizing environmental impacts. These findings encourage the adoption of agricultural practices that integrate organic amendments, contributing to more sustainable and eco-friendly farming systems.

Abbreviations

N	Nitrogen
P	Phosphorus
CK	Control (Without Amendment)
NPK	Nitrogen, Phosphorus and Potassium (Synthetic Fertilizers)
CSNPK	Crop Straw Plus Nitrogen, Phosphorus and Potassium (Synthetic Fertilizers)
BSNPK	Crop Straw Biochar Plus Nitrogen, Phosphorus and Potassium (Synthetic Fertilizers)

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Author Contributions

Hamidou Bah: Conceptualization, Investigation, Methodology, Writing – original draft

Adoté Hervé Gildas Akueson: Data curation, Software, Writing–original draft

Bo Zhu: Conceptualization, Funding acquisition, Supervision

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Fields

Hamidou Bah: Study of agricultural soil variability, Ecosystem conservation and biodiversity, Hydrology and water resource management, Pollution control, Field greenhouse gases monitoring, Agricultural non-point source pollution.

Adoté Hervé Gildas Akueson: Mathematical modeling of natural phenomena, Biomathematics applied to agricultural sciences, Forest estimation and sustainable forest management, Spatio-temporal analysis of forest populations, Impact of climate change on agriculture, Study of agricultural soil variability.

Bo Zhu: Agricultural ecosystem structure in hilly areas, Evolution process of purple soil fertility, C, N, P cycle and regulation of farmland ecosystem, Regulation of farmland ecosystem, Slope erosion process, Soil microorganisms and N, P transformation.