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Effect of Plow Pan on the Redistribution Dynamics of Water and Nutrient Transport in Soils

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Abstract: Plow pans are an essential part of the agricultural soil structure. By adjusting the soil bulk density and plow pan height, the water and nutrient transport are dynamically redistributed. Plow pans play a crucial role in promoting crop growth, increasing yields, and supporting sustainable land management. In this study, a column experiment was conducted to investigate the effects of plow pan height (10 cm and 15 cm) and bulk density (1.2, 1.4, and 1.6 g cm^{-3}) on soil nutrient and water leaching under high-volume (HV) and low-volume (LV) fertilizer applications. The results reveal that the leachate volume decreased by 61.9% at a plow pan height of 10 cm and by 96.2% at a plow pan height of 15 cm when the bulk density was increased from 1.2 to 1.4 g cm^{-3} under HV conditions. There was no leachate when the plow pan bulk density was 1.6 g cm^{-3}. The reserved concentration of alkali-hydrolyzable N in the plow pan soils was the highest when the plow pan had a bulk density of 1.4 g cm^{-3} and a height of 15 cm. However, when the plow pan height was 15 cm, the available P content in the plow pan soils decreased by 27.0% and 21.0% at bulk densities of 1.4 g cm^{-3} and 1.6 g cm^{-3}, respectively, when compared with 1.2 g cm^{-3}. Furthermore, the available P concentrations in the plow pan and subsoil layers decreased with an increase in the plow pan height. The available K concentrations in the topsoil decreased by 26.8% and 24.0% when the plow pan bulk density was increased from 1.2 to 1.4 g cm^{-3} at heights of 10 and 15 cm, respectively. Thus, the optimal plow pan height and bulk density are closely related to the types of soil nutrients. However, it is clear that excessively high bulk densities (e.g., 1.6 g cm^{-3}) negatively impact soil properties. For different nutrient requirements, a bulk density of 1.2 or 1.4 g cm^{-3} can be chosen, with each providing suitable options based on the specific nutrient needs. This research offers practical insights into changes in nutrient adsorption and fixation in agricultural production associated with alterations in plow pan bulk density.

Keywords: bulk density; leachate; soil layers; soil nutrients

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1. Introduction

A plow pan is a compacted soil layer under the tilling layer [1], resulting from long-term compression by agricultural activities and the deposition of clay particles [2,3]. The compaction of soil leads to a reduction in its porosity, which negatively affects its hydraulic conductivity, air permeability, and space availability. This further impedes the root expansion and water and nutrient absorption of plants [4]. Moreover, the reduced permeability of compacted soils increases the risk of soil erosion, which reduces soil fertility and poses a potential threat of environmental contamination in areas surrounding agricultural fields [5–7]. For example, compacted soils can lead to the erosion of 1100 tons km^{-2} of soil per year under specific agricultural conditions [8]. Plow pan soil, with high bulk density and low porosity, is similar to compacted soil, restricting the movement of water and air [9] and the penetration of crop roots [10,11]. For instance, a previous study found that the average height of the soybean root system reduced by 30.0% and that soybean biomass reduced by 20.0% in soil with a plow pan [12]. Soil porosity also decreased from 48% to 38% when the plow pan bulk density increased from 1.3 to 1.6 g cm^{-3} through the action of heavy machinery [13]. Moreover, plow pan height can affect nutrient leaching and agricultural productivity. A previous study found that nitrogen use efficiency was significantly higher in a 5 cm plow pan than in 10 cm and 15 cm plow pans. Meanwhile, the content of nutrients, such as organic carbon, total N, and available P in the soil, gradually decreased [14]. As the soil layer height increases, nutrient retention capacity improves [15].

Plow pan height can be modulated through different tillage practices, optimizing nutrient retention and reducing leaching losses. By adjusting the soil structure and profile, tillage practices control the water and nutrient movement in the soil, enhancing nutrient use efficiency and supporting sustainable agriculture [16]. A previous study found that reducing the soil bulk density decreased the leaching of NO_3^- and PO_4^{3-}, thereby mitigating environmental pollution [17]. Moreover, Li et al. showed that a thinner plow pan can lead to a higher crop N uptake and a greater N use efficiency than a thicker plow pan [18]. Therefore, changes in the plow pan bulk density are expected to alter soil physical properties (e.g., density, porosity, and permeability).

Previous studies have predominantly emphasized the impact of soil bulk density on singular aspects such as soil moisture, nutrients, and structure [19–21]. We conducted soil column leaching experiments to investigate the movement of soil nutrients and water, without the influence of climate and human activity. The knowledge of the effects of plow pan layer height and bulk density on nutrient retention in soils and leaching is limited. To bridge this gap, we conducted an experiment involving plow pans with various soil bulk densities and heights, systematically evaluating their effects on the fixation and leaching of nutrients by applying fertilizer solutions to soil columns. This research provides a more comprehensive understanding of the interaction between soil physical properties and agronomic practices in agricultural areas, as well as guidance on how to further enhance soil fertility by changing soil properties.

2. Materials and Methods

2.1. Soil

The soil used in the experiment was collected from a nursery garden, whose top layer was removed, in Jinhua, Zhejiang Province, China (29°4′48″ N, 119°38′24″ E). Roots and stones were removed and the soil was subsequently air-dried, crushed, and sieved through a 2 mm mesh. The soil properties were as follows: a pH of 5.74, an organic matter concentration of 13.7 g kg^{-1}, an alkali-hydrolyzable N concentration of 89.2 mg kg^{-1}, an available P concentration of 62.4 mg kg^{-1}, and an available K concentration of 108.2 mg kg^{-1}. The soil was classified as clay loam and comprised 18.1% clay (<0.002 mm), 31.5% silt (0.02–0.0002 mm), and 50.4% sand (2–0.02 mm).

2.2. Soil Column Leaching Experiment

A soil leaching test was conducted in an acrylic column (70 cm height × 10 cm diameter), which had a channel in the bottom center for leachate outflow (Figure 1). The air-dried soil was placed in the column to a height of 50 cm. All topsoil layers were 20 cm thick, and the plow pans had different heights and bulk densities. The experiment involved 6 treatments (Table 1) with 3 replicates, totaling 18 soil columns. We calculated the mass of the different soil layers with various bulk densities and heights; then, we compacted the soil with 60% of the maximum field water capacity in a separate column, which had a height of only 30 cm and from which the soil layers could be easily removed. Then, the soil layers were loaded into the column. Quartz sand with a height of 1 cm was placed on top of the topsoil to prevent the soil from being washed away. After the soil columns were filled, they were left to sit for 12 h before drip irrigation. According to the application rate of nitrogen fertilizer at 150 and 300 kg hm^{-2}, a low volume (LV) (392.5 mL, reaching a height of 5 cm in the column) of a fertilizer solution of N: P: K = 15:15:15 was applied to the soil column, and then a high volume (HV) (785.0 mL, reaching a height of 10 cm in the column) of the fertilizer solution was applied after two weeks. During this process, leachate was collected at various intervals until no water dripped for 2 h. After completing the leaching experiment, soil samples were collected according to the soil layers. The soil samples were air-dried and ground to 2 mm for a chemical analysis.

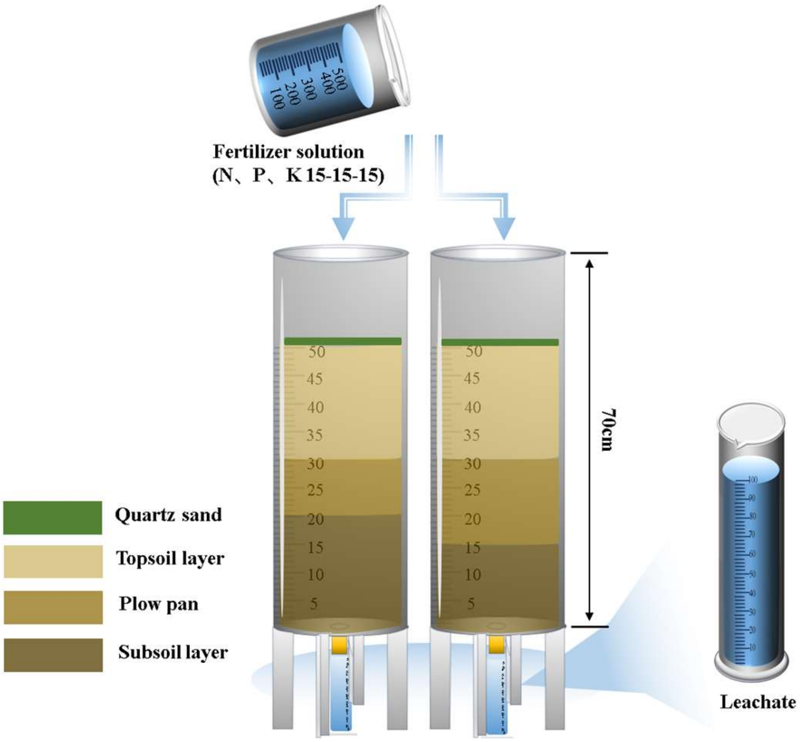

Figure 1. Schematic diagram of soil column leaching experiment.

Table 1. Treatments and properties of plow pan.

Treatment	Height (cm)	Bulk Density (g cm^{-3})	Saturated Hydraulic Conductivity (cm s^{-1})	Porosity of Plow Pan (%)
T1	10	1.2	4.2×10^{-3}	54.7
T2	10	1.4	1.8×10^{-4}	47.2
T3	10	1.6	/	39.6
T4	15	1.2	2.1×10^{-3}	54.7
T5	15	1.4	3.5×10^{-4}	47.2
T6	15	1.6	/	39.6

2.3. Physical and Chemical Analyses

Soil texture was determined using the hydrometer method. The soil sample was extracted using a dispersing agent at a ratio of 1:10 (m/v), and the mixture was left to stand overnight. Then, the percentages of sand, salt, and clay were determined by taking readings from a hydrometer in different time intervals [22]. Soil pH was determined in a soil solution with a 1:2.5 soil-to-water ratio using a pH meter (FiveEasy Plus; Mettler Toledo, Columbus, OH, USA). The organic matter content was determined using the potassium dichromate–sulfuric acid method: after heating the mixture, 0.5 mol L^{-1} ammonium ferrous sulfate solution was used for titration, and the organic matter content was calculated. Alkali-hydrolyzable N was extracted using 2.0 mol L^{-1} NaOH solution at a soil-to-solution ratio of 1:2. Then, 2% boric acid was used to absorb the released ammonia, and the residual solution was titrated using 0.01 mol L^{-1} sulfuric acid. The available P was extracted with

HCl–NH_4F solution at a soil-to-solution ratio of 1:10 for 0.5 h. Soil available K was extracted with 1.0 mol L^{-1} ammonium acetate at a soil-to-solution ratio of 1:10 for 0.5 h [23,24].

The total nitrogen (TN) concentrations in the leachate were determined by mixing the filtrate with an alkaline potassium persulfate solution at a 2:1 ratio and placing it in an autoclave for 30 min. The resulting solutions and alkali-hydrolyzable N in the supernatants were analyzed using a UV–visible spectrophotometer (T9; Persee, Beijing, China). The total phosphorus (TP) concentrations in the leachate were measured by mixing the filtrate with an alkaline potassium persulfate solution at a 25:4 ratio, followed by autoclaving for 30 min. The TP and available P concentrations were analyzed using the molybdenum blue method and determined using a UV–visible spectrophotometer (T9; Persee, Beijing, China). The total potassium (TK) concentrations in the leachate and available K in the soils were determined using an atomic absorption spectrophotometer (TAS-990AFG; Persee, Beijing, China) [25].

2.4. Data Statistics

The cumulative leaching amounts of TN, TK, and TP from the soil columns were calculated by multiplying the concentrations of TN, TK, and TP in the leachate by the volume of the leachate and summing these products. The calculation formula [26] is shown in Equation (1):

$$L = \sum_{i=1}^{n} \frac{Ci \times Vi}{10^3} \tag{1}$$

In the equation, L represents the cumulative leaching amount (mg) of TN, TK, and TP; C_i denotes the concentration (mg L^{-1}) of a certain nutrient in the ith leaching solution; and V_i indicates the volume (mL) of the ith leaching solution.

A calculation formula from [27] is shown in Equation (2):

$$K_s = \frac{Q}{A_t} \times \frac{L}{\Delta H} \tag{2}$$

In the equation, K_s indicates the saturated hydraulic conductivity (cm s^{-1}), Q indicates the volume of water passing through the soil sample (cm^3), L indicates the length of the soil sample (cm), A indicates the cross-sectional area of the soil sample (cm^2), H indicates the hydraulic head difference (cm), and t indicates the time (s).

A calculation formula from [27] is shown in Equation (3):

$$\phi = \frac{V_p}{V_t} \times 100\% \tag{3}$$

In the equation, ϕ represents the porosity (expressed as a percentage), V_p represents the pore volume, and V_t represents the total volume of the soil.

An experimental data analysis was performed using Microsoft Excel 2010 and IBM SPSS Statistics 26 software, while graphs were generated using Origin 2023 software. All plotted data are represented by arithmetic means and standard errors.

3. Results

3.1. Effect of the Height and Bulk Density of Plow Pan on Leachate Volumes

The leachate volume was saturated at 72 h in all treatments (Figure 2). The leachate volumes in the T1 and T4 treatments with the addition of the HV fertilizer solution were 261.0% and 113.0% higher than those with the addition of the LV fertilizer solution, respectively (Figure 2A,C).

The accumulated leachate volumes in T2 showed a continuous increase and peaked at 72 h (no leachate after this time). The leachate volumes were 129.0 mL and 250.0 mL, respectively, when the LV and HV fertilizer solutions were applied (Figure 2B). In T5, the leachate volume with the LV fertilizer solution showed a slow growing trend, reached its peak after 5 h, and then plateaued until the end; however, the leachate volume with the

HV fertilizer solution reached its peak earlier, after the 3rd hour, and then plateaued until the end, and the final volumes of both were approximately 20.0 mL. The leachate volumes decreased by 35.4% with the LV fertilizer solution and by 61.9% with the HV fertilizer solution when the bulk density was increased from 1.2 to 1.4 g cm^{-3} at a plow pan height of 10 cm (Figure 2A,B). However, the leachate volumes decreased by 84.2% with the LV fertilizer solution and by 96.1% with the HV fertilizer solution when the bulk density was increased from 1.2 to 1.4 g cm^{-3} at a plow pan height of 15 cm (Figure 2C,D).

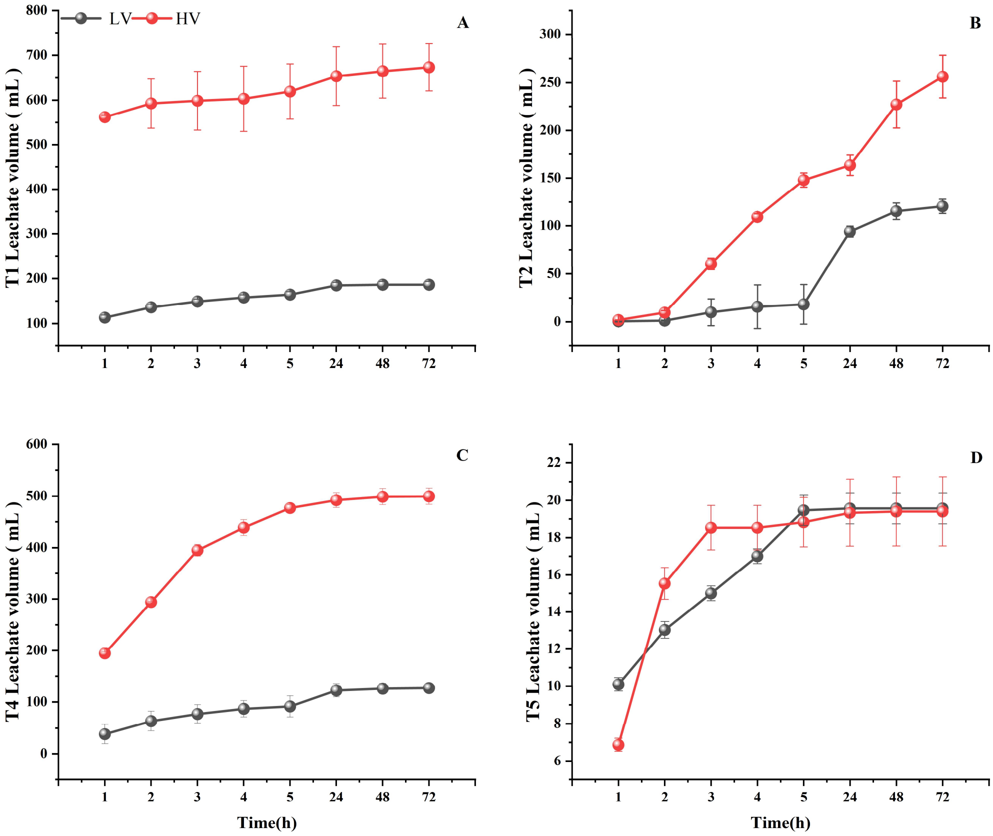

Figure 2. Accumulated leachate volumes over time in different treatments. Note: LV and HV represent the fertilizer solution volumes; (**A**,**C**) represent the accumulated leachate volumes at a bulk density of 1.2 g cm^{-3} when the height of the plow pan was 10 and 15 cm, respectively; (**B**,**D**) represent the accumulated leachate volumes at a bulk density of 1.4 g cm^{-3} when the height of the plow pan was 10 and 15 cm, respectively. There was no leachate in the T3 and T6 treatments.

3.2. Effect of Soil Bulk Density on Nutrient Concentrations in the Leachate

The increase in bulk density significantly reduced the TN concentrations in the leachate, by 42.0% and 49.3% at a plow pan height of 10 and 15 cm when the LV fertilizer solution was added, respectively ($p < 0.05$; Figure 3A). The TP concentration in the leachate did not significantly vary among the different treatments, irrespective of the plow pan height and bulk density (Figure 3B). The TK concentrations in the leachate reduced by 28.0% and 20.4% in T1 and T2 (at a plow pan height of 10 cm) with the addition of the LV fertilizer solution compared with the addition of the HV fertilizer solution ($p < 0.05$), respectively. However, they decreased by 18.0% and 6.0% in T4 and T5 (at a plow pan height of 15 cm), respectively. Significant differences were observed between the addition of LV and HV in the T2 and T5 treatments in terms of TK concentrations in the leachate ($p < 0.05$; Figure 3C) and in the T5 treatment in terms of TN concentrations in the leachate ($p < 0.05$).

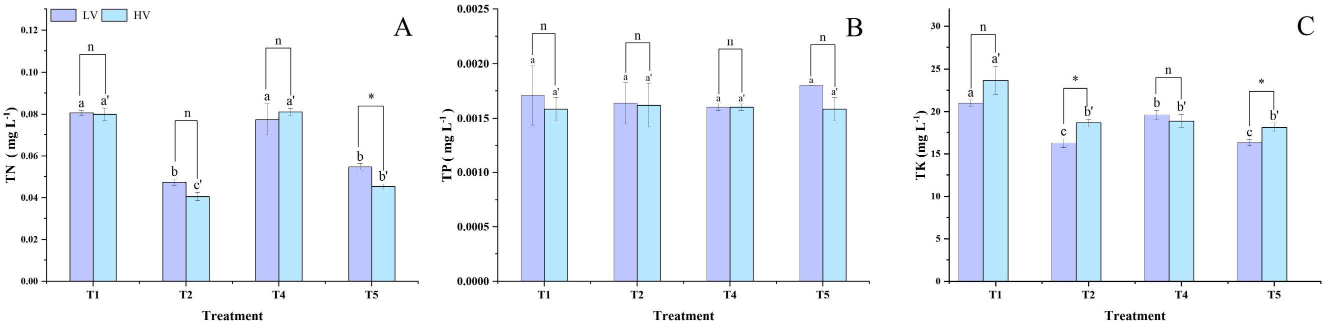

Figure 3. (**A**) TN, (**B**) TP, and (**C**) TK contents in the leachate of different treatments. Note: Different letters above the error bars indicate significant differences between 5 cm and 10 cm aqueous solutions under different treatments ($p < 0.05$). n and * indicate no significant difference and a significant difference between LV and HV in each treatment at $p < 0.05$, respectively.

3.3. Nutrient Contents in Different Soil Layers

The bulk density had no significant influence on the alkali-hydrolyzable N concentrations in the topsoil and subsoil layers (Figure 4, $p > 0.05$). The alkali-hydrolyzable N concentration in the plow pan increased with the bulk density when the height of the plow pan was 10 cm ($p < 0.05$, T1–T3), reaching 117.1 mg kg^{-1} at 1.6 g cm^{-3} in T3, which was 19.3% and 8.3% higher than in T1 and T2, respectively. However, the alkali-hydrolyzable N concentration was the highest at a bulk density of 1.4 g cm^{-3} (T5), when the height of the plow pan was 15 cm (T4–T6). Bulk density was the main influencing factor for enhancing the alkali-hydrolyzable N concentrations in the plow pan (Table S1).

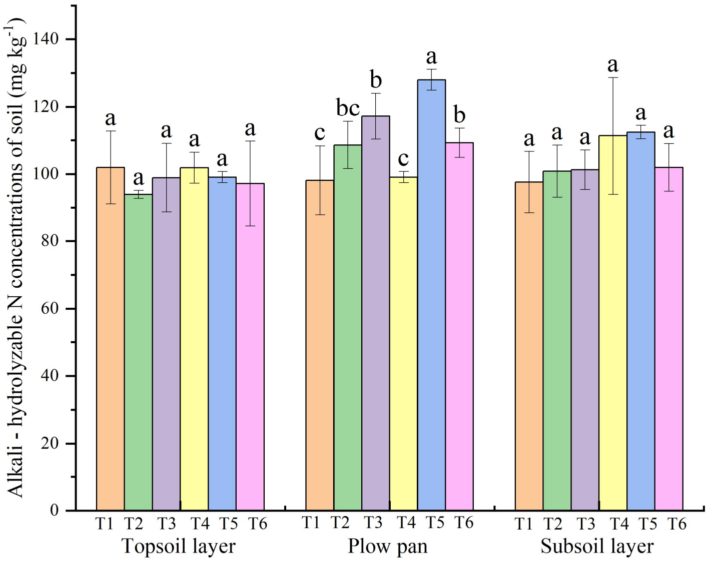

Figure 4. Alkali-hydrolyzable N concentrations in different soil layers. Note: different letters above the error bars indicate significant difference among treatments in the same soil layer ($p < 0.05$).

The increase in the plow pan bulk density caused various decreases in the available P concentrations at different plow pan heights. The available P concentration in the plow pan in T3 reduced by 27.3% compared with that in T1, while it reduced by 27.0% and 21.0% in T5 and T6, respectively, compared with that in T4 (Figure 5). A two-way ANOVA showed that the significant difference in the available P among treatments was related to the plow pan height and bulk density ($p < 0.05$; Table S2).

Changes in the plow pan height significantly affected the available K content (Table S3). The available K concentrations in the topsoil insignificantly decreased by 15.9% and 18.6% when the soil bulk density was increased from 1.2 to 1.6 g cm^{-3} at a plow pan height of

10 and 15 cm, respectively ($p > 0.05$; Figure 6). Moreover, a high plow pan height significantly decreased the available K concentration in the topsoil layer ($p < 0.05$; Figure 6); specifically, the available K concentrations at a bulk density of 1.2, 1.4, and 1.6 g cm^{-3} decreased by 26.8%, 24.1%, and 29.1%, respectively, when the plow pan height was increased from 10 cm to 15 cm. In addition, the available K concentration in the subsoil significantly decreased at a plow pan bulk density of 1.6 g cm^{-3} and height of 15 cm compared with the other treatments. There was no significant variation in the subsoil among the other treatments.

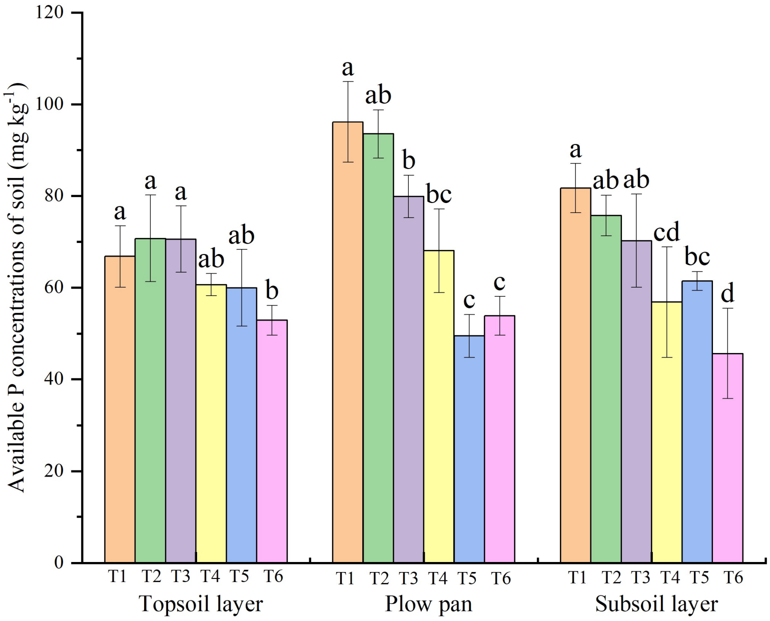

Figure 5. Available P concentrations in different soil layers. Note: different letters above the error bars indicate significant differences in the same soil layer ($p < 0.05$).

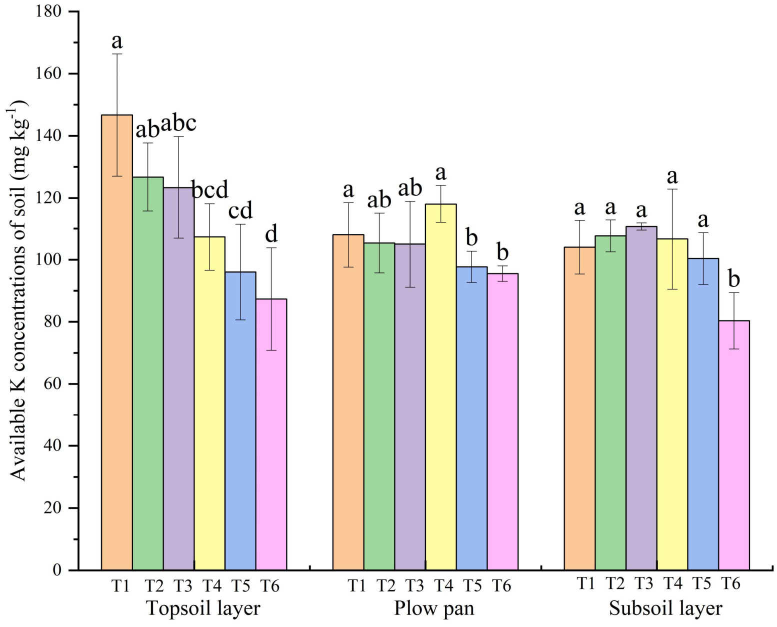

Figure 6. Available K concentrations in different soil layers after various treatments. Note: different letters above the error bars in each soil layer indicate significant differences among treatments ($p < 0.05$).

3.4. Redundancy Analysis

A redundancy analysis demonstrated a relationship among the leachate and soil nutrients and the plow pan bulk density and height (Figure 7). RDA1 (13.59%) and RDA2 (4.84%) were the two principal ordination axes and, together, explained 18.43% of the data variance. These axes illustrate the impact of environmental variables on leachate nutrient concentrations and soil physicochemical properties. P-B negatively correlated with TN, TP, and TK in the leachate, while H only correlated with TK in the leachate. FV pointed toward the positive direction of the RDA2 axis and showed a positive correlation with variables such as LV, AN, and AP. Conversely, FV negatively correlated with AN, AK, TN, TP, and TK in the soils.

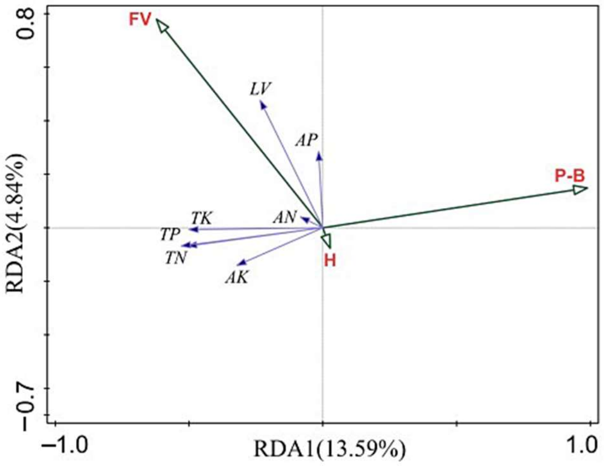

Figure 7. Redundancy analysis of nutrients in plow pan and leachate. Note: FV: volume of fertilizer solution; P-B: plow pan soil bulk density; H: plow pan height; LV: leachate volume; TN: total N concentrations in leachate; TP: total P concentrations in leachate; TK: total K concentrations in leachate; AN: alkali-hydrolyzed N concentrations in soil; AP: available P concentrations in soil; AK: available K concentrations in soil.

4. Discussion

4.1. Effect of Plow Pan on Leachate Volume and Nutrient Concentrations

In this study, the reduction in the leachate volume that is concomitant with the increase in the bulk density may be due to the decrease in soil porosity: demonstrated by the way in which the soil porosity decreased from 54.7% to 47.2% with the increase in the bulk density. This would impede the infiltration and permeability of water and nutrients [28,29]. A previous study has demonstrated that the total porosity and non-capillary porosity significantly decreased, by 3.4% and 5.0%, respectively, when the soil bulk density increased by 4.5% [30]. Moreover, a high bulk density reduces nutrient leaching by limiting the migration of small particles, such as soil colloids and microorganisms, which can adsorb and immobilize nutrients from the upper to the lower soil layers, thus increasing nutrient retention in the upper layers [31,32]. Therefore, the leachate nutrients and water are retained in soils, resulting in a decrease in the leachate volumes and nutrient concentrations [33,34]. In terms of TN, its concentration in the filtrate decreased as the plow pan height was increased. This can be attributed to the fact that an increased plow pan height prolongs the contact time of nitrogen and organic matter, leading to the adsorption and complexation of nitrogen by organic matter and thus reducing the TN in leachate [35]. In addition, microorganisms play a crucial role in nitrogen cycling and transformation in the soil, particularly through denitrification and anaerobic ammonia oxidation under anaerobic conditions, resulting in the loss of nitrogen and reducing the amount of nitrogen available for plant uptake [36]. Moreover, an increase in the bulk density reduces porosity and gas mobility, affecting the movement and exchange of potassium ions [37]. Phosphorus has low mobility in soil, primarily binding with iron and aluminum oxides or calcium ions to form insoluble compounds [38]. Thus, no significant differences in phosphorus mobility have been observed when bulk densities and plow pan heights are changed [39,40]. Consequently, the TP concentration in leachate also does not show significant differences. Although a high bulk density can reduce nutrient loss, an excessively high bulk density poses potential risks, such as reducing root penetration or even surface runoff, negatively impacting environmental sustainability [41,42]. A high bulk density also restricts oxygen diffusion and creates anaerobic conditions, thus decreasing microbial diversity and nutrient cycling [43].

4.2. Effect of Plow Pan on Nutrient Distribution in Soil Layers

Soil bulk density and layer height significantly influence nutrient fixation [44]. A high bulk density tends to increase nutrient fixation and availability [45]. The alkali-hydrolyzed N concentration gradually increased with the increase in the plow pan bulk density. This is primarily because an increased bulk density reduces soil porosity and aeration, which increases the soil water-holding capacity. The resulting anaerobic conditions promote anaerobic denitrifying bacterial metabolic processes that increase ammonia production, ultimately leading to higher levels of alkali-hydrolyzed N [46,47]. However, the plow pan height did not cause a significant difference in the alkali-hydrolyzable N concentration in the soils, which was attributed to the relative stability of alkali-hydrolyzed N in soil [48].

The plow pan height and bulk density had a slight impact on the available P in the topsoil layer; this was primarily attributed to the low bulk density of this layer (1.2 g cm^{-3}), which does not efficiently fix nutrients. In comparison, an increase in the plow pan bulk density and height led to a decrease in the available P concentration in the soil. This may be due to the transformation of orthophosphate into a less soluble form, a process known as phosphatization [49,50]. During leaching, available P may be redistributed through dissolution or, under certain conditions, converted into different forms of phosphate, thereby affecting the available P concentration in the soil [51]. High-volume fertilizer application promotes phosphorus fixation, particularly in soils with a high bulk density, where water movement is limited. This limitation can lead to phosphorus loss along specific pathways and increase the susceptibility of phosphorus to the formation of insoluble compounds with ions such as iron, aluminum, and calcium in certain microenvironments [52]. This exacerbates phosphorus fixation and reduces the available P.

The distribution of available K exhibited a surface accumulation phenomenon at a plow pan height of 10 cm. This may be due to the fact that the compaction of the plow pan can impede water mobility and result in the accumulation of K in topsoil [53]. However, there was no significant variation in the available K concentration between the plow pan and subsoil in all treatments. This may be due to the fact that potassium movement in soil primarily occurs through diffusion or mass flow and is strongly influenced by the soil water status [54]. Given the limitations of potassium diffusion in soil, changes in the bulk density or layer height may not significantly impact its horizontal movement or vertical distribution.

Overall, selecting an appropriate plow pan height and bulk density can decrease nutrient leaching and improve nutrient utilization, thereby reducing fertilizer use. This not only reduces costs but also improves crop yields, thereby enhancing economic sustainability. Additionally, reducing fertilizer application frequency contributes to environmentally friendly agricultural practices.

5. Conclusions

This study has revealed the influence of plow pan bulk density and layer height on nutrient retention and loss in soil. An increase in the plow pan bulk density decreases leaching rates, leachate volumes, and nutrient loss through alterations in soil porosity. A higher plow pan height increases the contact time between nutrients and soil, thereby enhancing the soil's capacity for nutrient fixation. However, excessively high bulk densities (e.g., 1.6 g cm^{-3}) negatively affect soil properties. In agricultural practice, a plow pan bulk density of 1.4 g cm^{-3} and height of 15 cm are recommended and could provide the highest alkali-hydrolyzable nitrogen content, thus being suitable for planting nitrogen-demanding crops (e.g., wheat, corn, and rice). Moreover, high-volume fertilizer application can reduce the TN and TP concentrations in leachate, leading to an increased fixation of both elements in the soil. This could improve nutrient utilization and thus reduce fertilizer use. In this study, an affective technique is proposed for agricultural practices, and guidelines are provided for choosing an appropriate plow pan height or bulk density to guarantee nutrient efficiency. However, as this experiment was conducted under ideal conditions, the results may not fully reflect the complex field environment. Field trials that consider influencing factors (e.g., climate and soil types) are recommended in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16208859/s1, Table S1: Two-way ANOVA of alkali-hydrolyzable N across soil layers; Table S2: Two-way ANOVA of available P across soil layers; Table S3: Two-way ANOVA of available K across soil layers; Table S4: Results of one-way ANOVA test: Post hoc multiple comparisons (Duncan's test) for alkali-hydrolyzable N in each soil layer.

Author Contributions: Conceptualization, M.Z. and S.D.; methodology, M.Z.; formal analysis, M.Z.; investigation, S.D.; resources, D.L.; data curation, M.Z.; writing—original draft preparation, M.Z.; writing—review and editing, L.H., H.C. and S.G.; visualization, M.Z.; supervision, D.L.; project administration, D.L.; funding acquisition, D.L. All authors have read and agreed to the published version of the manuscript.

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