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Biochar-amended and fertilized conditions influences nitrogen retention and loss dynamics: insights from a sandy loam soil column study

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Biochar-Amended and Fertilized Conditions Influences Nitrogen Retention and Loss Dynamics: Insights from a Sandy Loam Soil Column Study

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Abstract

Nitrogen (N) leaching from coarse-textured soils poses a significant environmental threat due to high permeability and inherently low nutrient exchange capacity, leading to groundwater degradation and diminished nitrogen use efficiency (NUE). Despite its potential, the depth-resolved and rate-dependent mechanisms governing the interaction between biochar amendments and inorganic N fertilizers remain inadequately characterized. This study evaluated the efficacy of corncob-derived biochar, in synergy with urea fertilizer, on the retention and leaching dynamics

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of ammonium (NH_4^+) and nitrate (NO_3^-) in sandy loam soil. A soil column experiment was conducted under controlled greenhouse conditions across six treatments: an unamended control, urea-only fertilizer, and urea combined with corncob biochar at application rates of 1%-4% (w/w). Biochar amendment significantly changed fundamental soil physicochemical properties, including soil pH, cation exchange capacity (CEC), and water retention capacity. Our results demonstrated that a 3% biochar application rate maximized NH_4^+ stabilization in subsoil layers, primarily driven by improved CEC. The 4% biochar treatment demonstrated the highest concentration of NO_3^- in the soil profile, while an increase in nitrate leaching was also noted. Principal Component Analysis (PCA) elucidated robust correlations between biochar-induced alterations (CEC, pH, and exchangeable cations) and N mobility, highlighting the divergent mechanisms regulating NO_3^- behavior. While biochar effectively immobilized NH_4^+, its influence on NO_3^- leaching was highly sensitive to application rates. These findings provide critical, depth-specific evidence for optimizing biochar-fertilizer formulations, emphasizing that tailored application rates are essential to balance nitrogen stabilization against leaching risks.

Keywords: Ammonium, Nitrate, Leaching, Nitrogen fertilizer, Biochar, Sandy loam soil

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1. Introduction

Nitrogen (N) is an essential macronutrient that underpins crop productivity and global food security; however, excessive N inputs have become a major source of environmental degradation in agroecosystems [1]. In intensive agricultural systems, a substantial proportion of applied nitrogen is not assimilated by crops but is instead lost through leaching, and runoff, leading to inefficient N use and severe environmental consequences [2]. These losses contribute to groundwater contamination, surface water eutrophication, soil salinization, and enhanced emissions of nitrous oxide (N_2O), a potent greenhouse gas [3], [4]. Therefore, developing cost-

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effective and sustainable strategies to improve nitrogen retention and minimize nitrogen losses in agricultural soils remains a critical challenge [1], [5].

Sandy soils are especially vulnerable to N losses due to their coarse texture, high permeability, and limited nutrient-holding capacity. These soils typically exhibit low water retention and CEC, resulting in rapid downward movement of water and dissolved nutrients beyond the root zone [6]. In Thailand, sandy soils occupy approximately 18,800 km^2, with nearly 80% of the northeastern plateau dominated by sandy and sandy loam textures [7]. Under such conditions, substantial portions of applied N fertilizers-particularly NH_4^+ and NO_3^- are prone to leaching, increasing the risk of groundwater contamination and downstream eutrophication [8]. Additionally, poor water retention in sandy soil exacerbates drought stress, further limiting crop productivity in rainfed and semi-arid regions [9].

Biochar, a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions, has gained increasing attention as a soil amendment capable of improving soil fertility while contributing to carbon sequestration [10]. Owing to its highly porous structure, large specific surface area, and abundance of surface functional groups, biochar exhibits strong adsorption capacity and physicochemical stability [11], [12]. Numerous studies have demonstrated that biochar application can enhance soil water retention, increase CEC, and improve nutrient availability, particularly in coarse-textured soils. In recent years, much attention has been directed on using biochar as a soil amendment to capture carbon while concurrently enhancing soil health. The configuration of biochar's small pores delineates its robust adsorption ability, little solubility, stable physical and chemical attributes, and extensive specific surface area [13], [14]. These properties suggest that biochar may play a crucial role in mitigating N losses from sandy soils.

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However, the retention mechanisms of N in biochar-amended soils differ between NH_4^+ and NO_3^-. The NH_4^+ retention is largely governed by cation exchange processes, with biochar's elevated CEC facilitating electrostatic adsorption of NH_4^+ ions [15]. Biochar typically possesses a negatively charged surface, potentially restricting the direct adsorption of NO_3^- via electrostatic interactions; consequently, nitrate retention on biochar may transpire through more intricate mechanisms, such as cation bridging, surface functional groups, or interactions with mineral constituents [16]. Previous studies have reported highly variable effects of biochar on NO_3^- dynamics, ranging from substantial reductions in nitrate leaching to negligible or even increased losses, depending on biochar feedstock, pyrolysis conditions, application rate, and soil type [17], [18]. For instance, Hazelnut husk biochar applications improved NO_3^- retention in surface soil layers, hence decreasing leaching in sandy soils [19]. Moreover, biochar-induced increases in soil pH may stimulate nitrification, potentially enhancing NO_3^- formation and subsequent leaching under high-permeability conditions [20].

Despite growing interest in biochar-based soil management, important knowledge gaps remain. In particular, the combined effects of biochar and inorganic nitrogen fertilizers on depth-specific NH_4^+ and NO_3^- retention and leaching in sandy loam soils are still insufficiently understood. Many existing studies have focused either on biochar alone or fertilizer inputs in isolation, while field-relevant scenarios typically involve their simultaneous application [10]. Furthermore, limited attention has been given to how varying biochar application rates influence N dynamics differently in topsoil and subsoil layers under controlled conditions.

Therefore, the objectives of this study were to (i) evaluate the effects of different application rates of corncob-derived biochar combined with N fertilizer on NH_4^+ and NO_3^- leaching in sandy loam soil, and (ii) investigate the relationships between biochar-induced changes

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in soil physicochemical properties and N retention at different soil depths. A soil column experiment was conducted under greenhouse conditions using N fertilizer applied at 1% (w/w), reflecting typical farmer practices, in combination with increasing biochar dosages. This study provides new insights into the rate-dependent and depth-specific roles of agricultural waste-derived biochar in regulating nitrogen dynamics in sandy loam soils. The findings are expected to support the development of more sustainable fertilizer management strategies aimed at reducing N losses and protecting groundwater and surface water resources in vulnerable agroecosystems.

2. Materials and methods

2.1 Raw material and pre-treatment

Corncob was selected as the feedstock for biochar production due to its abundance as an agricultural leftover from maize cultivation, a principal crop in northern Thailand, especially in Chiang Mai Province. Substantial amounts of corncob and other maize byproducts are frequently incinerated in open fields post-harvest, considerably exacerbating seasonal haze events and increasing air pollution in the area. The corncobs were obtained from the Highland Agricultural Research Station at Chiang Mai University, Thailand. The collected corncobs were first thoroughly washed with deionized (DI) water to remove adhering soil particles, dust, and other surface impurities. The washed biomass was then air-dried under sunlight for several days. The dried corncobs were then kept in plastic bags for later conversion into biochar.

2.2 Biochar production

The prepared corncob biomass was subsequently subjected to pyrolysis in a traditional kiln following the method described in our previous study [21]. The corncobs were pyrolyzed at a temperature ranging from 400℃ to 550℃ for a 4-h heating period to promote the formation of

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stable carbon structures and enhance the development of porous characteristics in the biochar. After completion of the pyrolysis process, the traditional kiln was allowed to cool naturally to room temperature under a closed condition to prevent oxidation of the produced biochar. The resulting corncob biochar was then collected and mechanically crushed using a laboratory grinder. The ground biochar was subsequently sieved through a 2 mm mesh sieve to obtain uniform particle size for experimental consistency. The produced biochar samples were stored in airtight containers at room temperature prior to physicochemical characterization and subsequent leaching experimental applications.

2.3 Corncob biochar characterizations

The pH and electrical conductivity (EC) of the corncob biochar were determined using a previous study [22]. Cation exchange capacity (CEC) was determined followed by the published study [23]. Total nitrogen (TN) by dry combustion was analyzed using an elemental analyzer (CHN-O-RAPID, Heraeus, Hanau, Germany). The concentration of exchangeable cations (K^+, Ca^{2+}, and Mg^{2+}) in biochar was determined with 1 M NH_4OAc (1:10 w/v) using Atomic Absorption Spectrophotometry (AAS, Model contrAA 800/Analytik Jena, Germany). The surface morphology and elemental composition of the corncob biochar were analyzed using high-resolution field emission scanning electron microscopy (FE-SEM) coupled with an energy-dispersive X-ray spectroscopy (EDS) detector (Thermo Scientific Apreo S, USA). The surface functional groups of the biochar were characterized using Fourier-transform infrared spectroscopy (FTIR) (PerkinElmer Spectrum GX, USA). The FTIR spectra was recorded over a wavenumber range of 4000-400 cm^{-1} to identify the major functional groups present on the produced biochar surface.

2.4 Soil characterization

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Prior to the experiment, soil samples were air-dried, homogenized, and passed through a 2 mm sieve. Soil pH was measured using an Eutech pH 2700 meter in a soil-to-water suspension at a ratio of 1:2 (w/v), following the method adapted from [24]. Soil EC was measured using a ratio of soil with water suspensions (1:5 v/v). Soil CEC was measured following the method of previous method [23]. The soil textures (sand, silt, and clay) were analyzed by the hydrometer method for particle size analysis [25]. Soil organic matter was measured using the wet oxidation method [26]. Soil organic carbon was computed by multiple 0.58 with percentage of soil organic matter. Exchangeable cations (K^+, Ca^{2+}, and Mg^{2+}) were measured using 1 N NH_4OAc (pH 7.0). The exchangeable cations concentration was analyzed by AAS. Available P was extracted by the Bray II method [27], and the absorbance was determined at 882 nm using a Thermo Genesys 20 spectrophotometer.

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2.5 Site description and experimental design

The experiment was conducted in a greenhouse at the Faculty of Agriculture, Chiang Mai University, Thailand. The study was carried out during the cool and dry seasons from October 2023 to April 2024, with average ambient greenhouse temperatures ranging between 25-30°C and average relative humidity approximately 71.3% throughout the experiment. The experiment followed a completely randomized design (CRD) consisting of six treatments with three replications each. The treatments were defined as follows:

1) S: soil only (control)

2) SF: soil amended with 1% urea fertilizer (w/w)

3) SFB1: soil amended with 1% urea fertilizer and 1% corncob biochar (w/w)

4) SFB2: soil amended with 1% urea fertilizer and 2% corncob biochar (w/w)

5) SFB3: soil amended with 1% urea fertilizer and 3% corncob biochar (w/w)

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6) SFB4: soil amended with 1% urea fertilizer and 4% corncob biochar (w/w)

Polyvinyl chloride (PVC) columns with an outer diameter of 17 cm and a height of 65 cm were used as soil containers. The PVC column had an inner diameter of 4 cm. Each column was constructed to simulate soil profile layers, consisting of a 25 cm irrigation zone at the top, followed by a 20 cm topsoil layer and a 20 cm subsoil layer. To assess the vertical distribution and retention of inorganic nitrogen within the soil profile, the topsoil and subsoil-both of which were categorized as sandy loam were collected at varying depths. A perforated base covered with filter paper and gravel was installed at the bottom of each column to facilitate drainage and leachate collection while preventing soil loss.

Prior to column packing, the air-dried and sieved soils were thoroughly mixed with corncob biochar at the designated application rates. The mixtures were homogenized to ensure uniform distribution of biochar throughout the soil matrix. The N fertilizer application rate of 1% (w/w) was selected as an experimental level used in controlled soil amendment studies to study nitrogen dynamics and interactions between biochar and fertilizer. The control treatment received neither nitrogen fertilizer nor biochar.

Soil was packed into the columns to approximate the natural bulk density of the field soil. The subsoil layer was packed first, followed by the topsoil layer. After packing, the columns were gradually saturated with DI water to stabilize soil structure and eliminate air pockets. Throughout the experimental period, soil moisture was maintained at approximately 60% of field capacity by applying DI water at regular intervals. The irrigation water was applied evenly to the top irrigation zone to simulate natural infiltration. Leachate samples were collected from the column outlets at 0, 7, 14, 21, 28, and 45 days after treatment application for nutrient analysis. Meanwhile, soil

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samples were collected separately from the topsoil and subsoil for nutrient analysis. The temperature range was about 30 – 35 ^{o}C throughout the experiment.

2.6 Leachate collection and analysis

Prior to treatment application, soil columns were pre-incubated with 290 mL of DI water for 14 days to stabilize soil moisture conditions and promote microbial acclimatization. This pre-incubation step was conducted to minimize transient effects associated with soil disturbance during column packing. During the experimental period, the total leachate volume from the column was recorded to evaluate changes in soil water-holding capacity following corncob biochar amendment. Irrigation was performed by uniformly applying 60 mL of DI water to the top irrigation zone of each column to simulate rainfall or infiltration events. Leachate was collected immediately after each irrigation event using plastic collection containers placed beneath the column outlets. Sampling was conducted at 0, 7, 14, 21, 28, and 45 days after treatment application. The collected leachate volume was measured and recorded for each sampling interval to assess water retention characteristics under different treatment conditions. Leachate samples were subsequently transferred into sterile 50 mL polypropylene containers and transported to the laboratory under controlled conditions. The samples were filtered through 2.5 µm filter paper to remove suspended particles and prevent further microbial or chemical transformation. After filtration, the samples were stored at 4°C prior to chemical analysis to preserve sample integrity. All leachate samples were analyzed within an appropriate holding time to minimize alterations in nutrient concentrations. The leachate samples were analyzed for NH_4^+, NO_3^-, available P, and exchangeable cations. The NH_4^+ concentrations were determined using a standard colorimetric technique [28]. While NO_3^- concentrations were measured using salicylic acid technique [29].

2.7 Statistical analysis

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Differences among treatments in soil properties and nutrient leaching, including NH_4^+ and NO_3^- concentrations, were evaluated using one-way analysis of variance (ANOVA). When significant differences were detected, mean comparisons among treatments were performed using the Least Significant Difference (LSD) test at a significance level of $p \leq 0.05$. All statistical analyses were conducted using Statistix software (version 10.0, Analytical Software, Tallahassee, FL, USA). Data visualization and graphical presentations were generated using SigmaPlot software (version 15.0, Systat Software Inc., San Jose, CA, USA). Principal component analysis (PCA) was performed using standardized variables to evaluate multivariate relationships between nutrient leaching parameters and soil physicochemical properties and to identify the principal factors governing nutrient transport.

3. Results

3.1 Characteristics of corncob biochar and soil properties

To study the ability of the produced biochar on the nutrient leaching in sandy loam soil, the initial characteristics of corncob biochar and soil samples were investigated. The characteristics of soil properties are presented in Table 1. The original soil sample (S) was slightly acidic soil with the pH of 5.91 ± 0.05 and EC of 1.00 ± 0.07 dS m^{-1}. It was characterized as a soil texture with the highest sand particle of 70% followed by silt (26%) and clay (4%), respectively. The CEC of the S soil sample was 10.92 ± 0.04 cmol kg^{-1}. The soil organic matter (SOM) and soil organic carbon (SOC) contents were 4.01 ± 0.14% and 2.15 ± 0.24%, respectively. The concentrations of exchangeable K, Ca, and Mg were 297.58 ± 6.07, 321.64 ± 8.65, and 111.28 ± 1.18 mg kg^{-1}, respectively.

The properties of produced corncob biochar have a direct impact on the practical application of produced corncob biochar on nutrient leaching function. The physical and chemical

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characteristics are described in our previous published article [30]. Briefly, the produced corncob biochar is strongly alkaline with the pH of 9.69 ± 0.01 and EC of 0.43 ± 0.04 dS m^{-1}. The biochar also contained CEC with 34.10 ± 0.25 cmol kg^{-1}. In addition, it exhibited a significant organic matter concentration of 17.84 ± 0.26%, alongside an organic carbon content of 9.71 ± 0.14%. Corncob biochar revealed exchange concentration of K^+, Ca^{2+}, and Mg^{2+} at 0.96 ± 0.28 mg kg^{-1}, 18.94 ± 0.11 mg kg^{-1}, and 1.00 ± 0.01 mg kg^{-1}, respectively.

To investigate the surface properties of the produced biochar, the functional groups of the corncob biochar were characterized (Fig. 1a). The FTIR spectra reveals various functional groups present on the corncob biochar. The peak at 555 cm^{-1} was attributed to the C–H stretching vibrations [31], while the bands observed at 747–871 cm^{-1} were assigned to the out-of-plane deformation vibrations of aromatic C–H bonds [32]. The peak at 1046 cm^{-1} was associated with the C–N stretching vibrations of amide groups [33]. The band at 1360 cm^{-1} can be assigned to C–O bond associated with hydroxyl, ester, and ether functional groups [34]. The presence of C–C stretching vibrations around 1566 cm^{-1} are attributed to the depolymerization and dehydration of materials due to pyrolysis, which results in the formation of C–C double bonds. The peak at 2845 cm^{-1} and 2909 cm^{-1} responded to symmetric and symmetric C–H stretching vibrations in aliphatic CH, CH_2, and CH_3 [35]. Corncob biochar also presented intensity peaks at 3866 and 3743 cm^{-1} which ascribed to free OH and phenol O–H [36].

The surface morphology and pore size structure of corncob biochar are critical factors influencing its ability to reduce soil nutrient leaching. Therefore, the morphological features and porous structure of the sample were investigated, as shown in Fig. 1(b). The SEM image reveals a well-developed honeycomb-like morphology with a distinct pore size distribution on the surface of the corncob biochar. The measured pore diameters of the biochar were approximately 30.92

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μm, 22.99 μm, and 14.36 μm. EDS is a crucial analytical technique for determining the elemental composition and spatial distribution of elements in biochar. The results indicate that the corncob biochar is predominantly composed of carbon (87.1%), along with appreciable amounts of oxygen (10.9%) and potassium (0.9%) (Fig. 2(a)). The corresponding scanned area used for the EDS analysis is shown in Fig. 2(b). Elemental mapping further confirms that the biochar surface contains C, O, K, Si, Mo, P, Al, and Cl, all of which are homogeneously distributed across the biochar matrix (Figs. 2(c) - 2(j)).

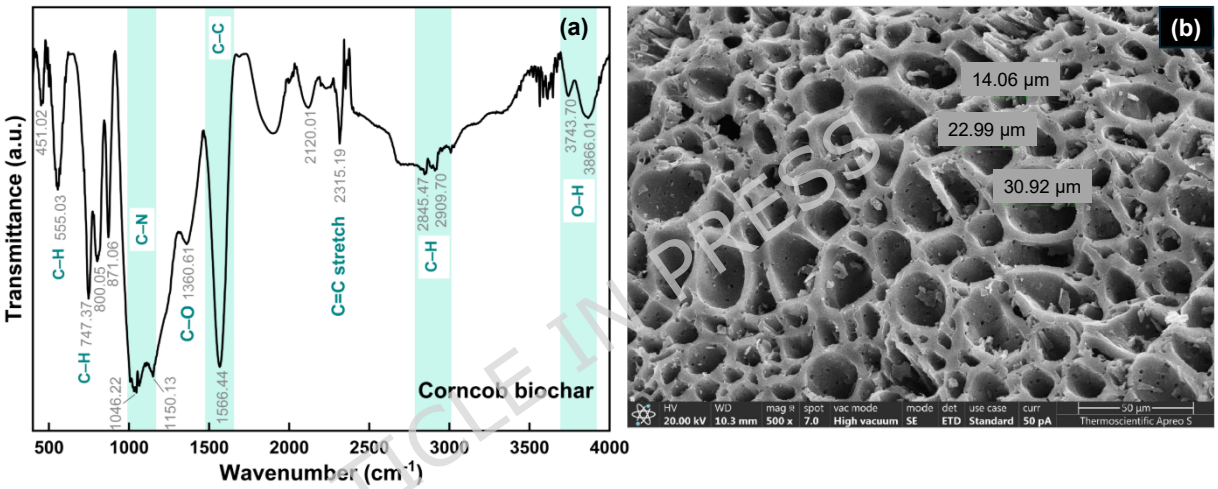


Fig. 1. (a) FTIR spectrum and (b) SEM micrograph of corncob biochar at 500x magnification.

Table 1 Physical and chemical characteristics of initial soil sample.

Properties	Soil values
pH	5.91 ± 0.05
EC (dS m^{-1})	1.00 ± 0.07
Sand (%)	70

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Silt (%)	26
Clay (%)	4
Soil texture classification	Sandy loam
CEC (cmol (+) kg^{-1})	10.92 ± 0.04
Soil organic matter (%)	4.01 ± 0.14
Soil organic carbon (%)	2.15 ± 0.24
K^{+} (mg kg^{-1})	297.58 ± 6.07
Ca^{2+} (mg kg^{-1})	321.64 ± 8.65
Mg^{2+} (mg kg^{-1})	111.28 ± 1.18

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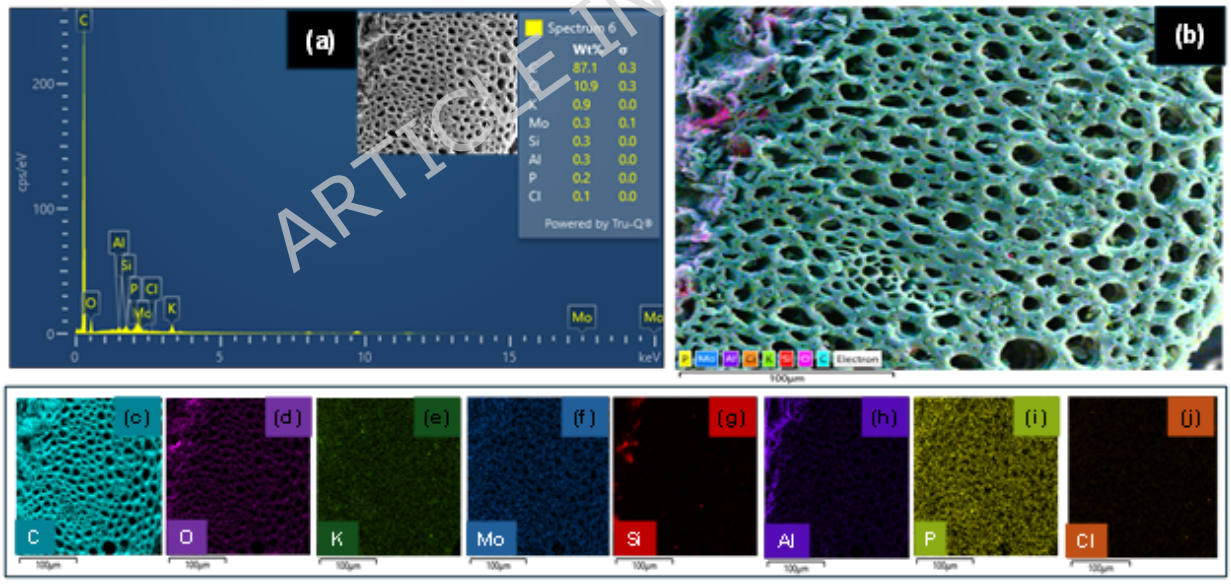


Fig. 2. EDS characterization of corncob biochar: (a) EDS spectrum, (b) corresponding scanned area, and elemental mapping of (c) C, (d) K, (e) O, (f) P, (g) Mo, (h) Cl, (i) Al, and (j) Si.

3.2 Influence of corncob biochar application rate on soil properties

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To evaluate the impact of corncob biochar application rates combined with nitrogen fertilization on NH_4^+ and NO_3^- leaching, the physicochemical properties of both topsoil and subsoil were characterized (Table 2). Following a 45-day incubation, soil pH increased across all biochar-amended treatments in both soil layers. In the topsoil, pH values were significantly higher in biochar-treated groups compared to the control ($p < 0.05$), which exhibited the lowest alkalinity. While biochar amendment notably raised pH relative to the baseline soil, differences between the fertilizer-only (SF) and biochar-amended fertilizer groups (SFB1–SFB4) did not reach statistical significance. Despite an initial soil pH of 5.9, the pH of the control soil rose to 6.86 in the topsoil and 6.74 in the subsurface following the study period. This increase may be linked to soil equilibration under regulated moisture conditions during the column experiment.

Soil EC in the topsoil increased under SFB1, SFB3, and SFB4 treatments, though a reduction was observed at the 2% application rate (SFB2). Conversely, subsoil EC increased across all biochar treatments, with significant variations noted specifically in SFB2, SFB3, and SFB4. The increase may be ascribed to the leaching and downward migration of soluble salts and base cations (e.g., K^+, Mg^{2+}, and Ca^{2+}) from the biochar into the soil profile, thus elevating soil EC. Moreover, biochar can improve nutrient retention and cycling due to its porous structure and mineral-rich content [37]. Biochar amendment significantly enhanced the soil CEC; this effect was most pronounced in the subsoil at 2% and 3% dosages, whereas the 4% dosage led to a relative decline. Regarding nutrient availability, phosphorus (P) concentrations peaked at application rates of 3% (35.40 ± 0.77 mg kg^{-1}) and 4% (34.73 ± 0.64 mg kg^{-1}). This increase may be ascribed to the direct input of phosphorus from biochar and indirect effects via elevated soil pH, reduced phosphorus fixation, and improved phosphorus desorption, leading to enhanced phosphorus availability for plant absorption [38]. However, these values were not statistically distinct from the control, and no

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significant trends in available P were observed in the subsoil across different dosages. Exchangeable potassium (K) in the topsoil was highest in the SFB1 treatment (60.68 ± 0.97 mg kg^{-1}), though it did not differ substantially from the SF group. Similarly, while SFB1 yielded the highest exchangeable K in the subsoil, differences between the S, SF, and SFB4 treatments remained negligible. Finally, exchangeable calcium (Ca) significantly peaked in topsoil treatments SFB3 and SFB4 (2071 ± 66.46 mg kg^{-1} and 2272 ± 17.39 mg kg^{-1}, respectively), whereas exchangeable magnesium (Mg) reached its maximum in SFB3 for both topsoil (171.81 ± 8.04 mg kg^{-1}) and subsoil (163.42 ± 7.21 mg kg^{-1}).

3.3 Dynamics of NH_4^+ and NO_3^- retention in biochar-amended soil

As no nitrogen fertilizer was used, the lower NH_4^+ concentrations seen in the S treatment were expected. Thus, by contrasting the fertilized treatments (SF and SFB1-SFB4), the impact of biochar on nitrogen retention was assessed. Variations in NH_4^+ concentrations across these treatments imply that the application of biochar affected the dynamics and retention of nitrogen in the soil column. The incorporation of corncob biochar significantly modulated the retention profiles of ammonium (NH_4^+) and nitrate (NO_3^-) within the sandy loam matrix (Figs. 3a - 3d). In the topsoil, the SFB3 treatment demonstrated the highest NH_4^+ retention (approximately 11 mg kg^{-1}), representing a significant enhancement over the majority of experimental groups ($p < 0.05$). This suggests a synergistic effect between mineral fertilization and biochar amendment in stabilizing NH_4^+ in the upper soil horizon (Fig. 3a). Notably, however, the retention capacity of SFB3 was statistically comparable to that of the fertilizer-only (SF) treatment, indicating that the relative contribution of biochar to NH_4^+ immobilization in the topsoil may be dosage-dependent. A more pronounced effect was observed in the subsoil (Fig. 3b), where NH_4^+ concentrations were substantially higher across all treatments. The SFB3 amendment achieved a peak retention of

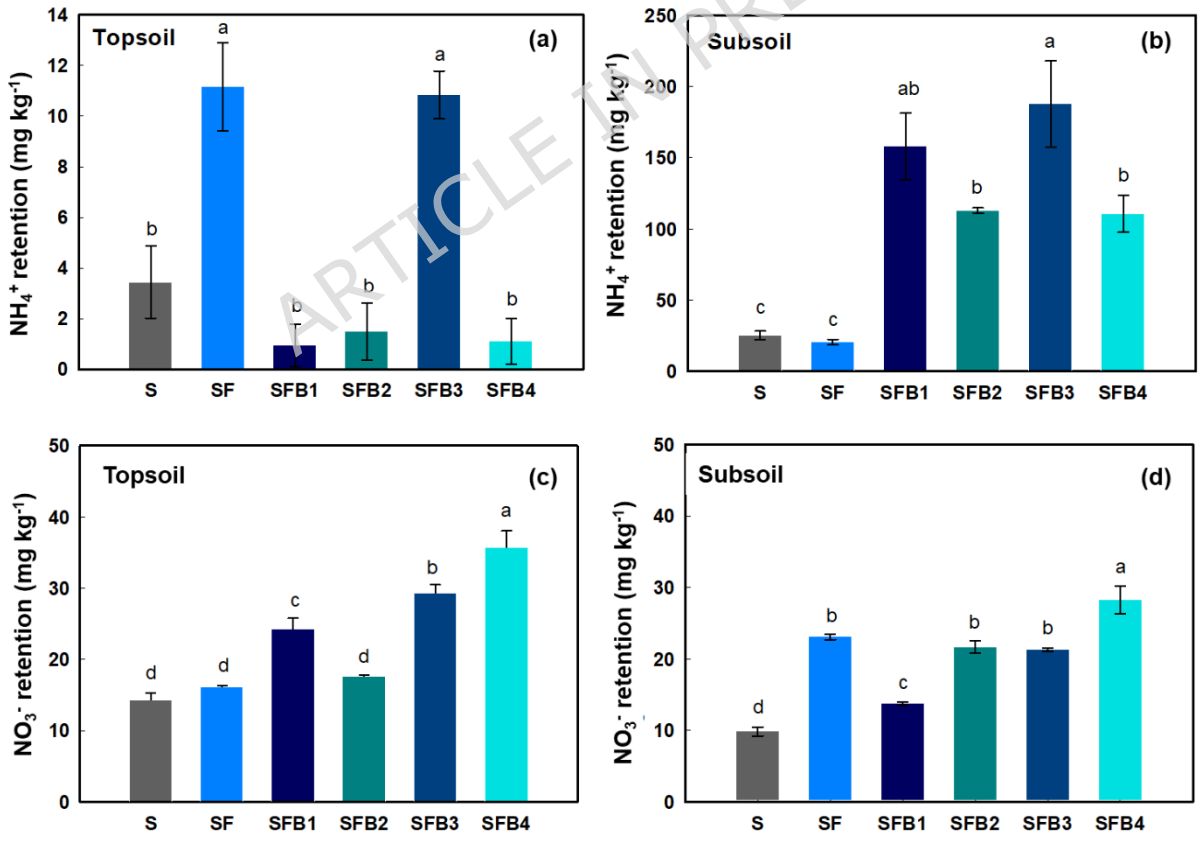
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187.76 mg kg^{-1}, significantly outperforming both the control (S) and SF groups ($p < 0.05$). While the SFB1 treatment exhibited high retention levels, the difference between SFB1 and SFB3 did not reach statistical significance. In contrast, the S and SF treatments consistently yielded the lowest NH_4^+ values, corroborating that biochar application-particularly at the 1% and 3% rates-effectively mitigates the downward migration of NH_4^+ by enhancing the soil's cation sorption capacity. Regarding nitrate dynamics, the SFB4 treatment (4% application rate) exhibited superior NO_3^- retention in the topsoil (35 mg kg^{-1}), significantly surpassing all other treatments (Fig. 3c). While moderate retention was observed in SFB1 and SFB3, the significantly lower values in the S, SF, and SFB2 groups highlight the efficacy of higher biochar dosages in sequestering highly mobile NO_3^- ions. This trend persisted in the subsoil (Fig. 3d), where SFB4 maintained the highest NO_3^- levels (approximately 30 mg kg^{-1}), followed by SF and SFB2. Conversely, the S and SFB1 treatments showed minimal retention, suggesting higher susceptibility to leaching. Collectively, these findings indicate a differential response of inorganic nitrogen species to corncob biochar: while moderate application rates (1-3%) are optimal for NH_4^+ stabilization, higher application rates (4%) are requisite for effective NO_3^- attenuation across the soil profile. These results demonstrate that corncob biochar functions as an effective soil conditioner for nitrogen stabilization, with its efficacy being highly dependent on the target ionic species and application dosage. The distinct retention patterns observed suggest that while moderate amendments optimize NO_3^- sequestration, higher dosages are essential to counteract the high mobility of nitrate in sandy loam profiles. Consequently, the strategic integration of corncob biochar at a 3-4% application rate provides solid evidence for enhancing nitrogen usage efficiency and reducing environmental hazards linked to nutrient leaching. The distinct retention patterns observed suggest that the mechanisms governing NH_4^+ and NH_3^- retention differ substantially. NH_4^+, as a cation, can be directly adsorbed onto

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negatively charged surfaces of biochar and retained through enhanced CEC, resulting in effective retention at moderate biochar application rates (1–3%) [37]. In contrast, NO_3^-, an anion, exhibits high mobility in sandy loam soil and is not readily retained by cation exchange sites. Consequently, elevated biochar application rates (3-4%) are necessary to enhance NO_3^-retention by augmenting porosity and water-holding capacity, so jointly diminishing NO_3^- leaching losses [38], [39].

Nonetheless, direct comparisons of nutrient leaching and soil chemical characteristics between topsoil and subsoil after the application of mixed biochar and fertilizers remain comparatively few. Previous studies have reported the reduction of nitrogen leaching after co-application of biochar and mineral fertilizer [40]. The impacts of biochar and nitrogen fertilizer across the soil profile demonstrate varying reactions between topsoil and subsoil layers [41].



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Fig. 3. Retention of NH_4^+ in (a) topsoil and (b) subsoil, and NO_3^- in (c) topsoil and (d) subsoil across different treatments. Values followed by different letters within each panel indicate statistically significant differences ($p < 0.05$, LSD test), while identical letters indicate no significant difference.

Table 2 The soil properties after treated with different corncob biochar application for 45 days.

Treatment	pH	EC ($\mu S\ m^{-1}$)	CEC (cmol (+) kg^{-1})	Available P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg
Topsoil						
S	6.86 ± 0.06^{c}	0.13 ± 0.00^{abc}	48.00 ± 2.48^{a}	32.95 ± 1.51^{ab}	37.12 ± 1.65^{c}	1888 ± 45.8
SF	7.57 ± 0.03^{b}	0.12 ± 0.00^{bc}	24.06 ± 2.71^{d}	30.47 ± 2.27^{b}	63.37 ± 1.37^{a}	1804 ± 11.7
SFB1	7.58 ± 0.03^{ab}	0.14 ± 0.01^{abc}	26.16 ± 2.91^{cd}	32.94 ± 0.47^{ab}	60.68 ± 0.97^{a}	1980 ± 12.3
SFB2	7.72 ± 0.08^{ab}	0.12 ± 0.01^{c}	31.93 ± 2.90^{c}	33.96 ± 0.46^{ab}	41.12 ± 1.84^{c}	1910 ± 39.9
SFB3	7.71 ± 0.01^{ab}	0.17 ± 0.01^{a}	40.60 ± 1.84^{b}	35.40 ± 0.77^{a}	37.62 ± 1.94^{c}	2071 ± 66.4
SFB4	7.63 ± 0.10^{ab}	0.16 ± 0.01^{ab}	30.40 ± 0.23^{cd}	34.73 ± 0.64^{a}	52.26 ± 2.15^{b}	2272 ± 17.3
Subsoil						
S	6.74 ± 0.06^{b}	0.18 ± 0.00^{b}	25.05 ± 4.70^{cd}	33.18 ± 1.58^{a}	60.31 ± 2.13^{a}	2248 ± 3.60
SF	7.99 ± 0.01^{a}	0.17 ± 0.01^{b}	24.70 ± 0.75^{cd}	34.94 ± 1.69^{a}	59.62 ± 1.97^{a}	2157 ± 16.2
SFB1	7.97 ± 0.05^{a}	0.18 ± 0.00^{b}	22.70 ± 3.42^{d}	32.08 ± 1.12^{a}	60.43 ± 0.68^{a}	1841 ± 17.2
SFB2	8.07 ± 0.10^{a}	0.22 ± 0.00^{a}	49.82 ± 2.38^{a}	32.78 ± 0.37^{a}	46.18 ± 2.77^{b}	2073 ± 5.70
SFB3	8.04 ± 0.05^{a}	0.24 ± 0.01^{a}	42.65 ± 4.30^{ab}	34.51 ± 0.23^{a}	38.15 ± 1.93^{c}	2296 ± 98.2
SFB4	7.97 ± 0.04^{a}	0.22 ± 0.00^{a}	34.56 ± 2.28^{bc}	32.51 ± 1.19^{a}	55.25 ± 2.30^{a}	2152 ± 68.0

Note: Different letters indicate statistically significant differences ($p<0.05$) of each column of topsoil and subsoil.

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3.4 Temporal dynamics of NH_4^+ and NO_3^- leaching under biochar amendment

The effectiveness of corncob biochar in regulating NH_4^+ and NO_3^- leaching from sandy loam soil was evaluated over a 45-day incubation period. Temporal variations in total NH_4^+ and NO_3^- leaching under different biochar application rates are presented in Fig. 4a and Fig. 4b, respectively. Total NH_4^+ leaching exhibited pronounced treatment- and time-dependent responses (Fig. 4a). During the early incubation stage, the incorporation of corncob biochar markedly reduced NH_4^+ leaching compared with the fertilizer-only treatment, indicating enhanced ammonium retention following biochar amendment. Among the biochar treatments, SFB3 showed significantly higher cumulative NH_4^+ leaching than the other biochar-amended soils, whereas SFB4 consistently maintained lower NH_4^+ losses. Significant differences among treatments were observed after 45 days of incubation ($p < 0.01$). Although the unamended soil (S) exhibited the lowest NH_4^+ leaching throughout the experimental period, this was attributed to limited nitrogen availability rather than improved retention capacity. These results indicate that biochar application rate plays a critical role in controlling ammonium mobility, with moderate application rates potentially promoting NH_4^+ retention more effectively than higher rates.

In contrast, NO_3^- leaching displayed a distinct temporal pattern in response to biochar amendment (Fig. 4b). Total NO_3^- leaching declined significantly within the first 7 days following biochar application, suggesting short-term immobilization or delayed nitrification. During the intermediate incubation period, NO_3^- leaching remained relatively stable across treatments. However, a secondary increase in NO_3^- leaching was observed after 28 days and persisted until the end of the experiment. Notably, biochar-amended treatments, particularly at higher application rates (SFB3 and SFB4), exhibited greater cumulative NO_3^- leaching than the unamended soil, indicating that increased biochar dosage does not necessarily mitigate nitrate losses under sandy

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loam conditions. Overall, these findings demonstrate contrasting, rate-dependent responses of NH_4^+ and NO_3^- to corncob biochar amendment. While biochar effectively reduced ammonium leaching during the early incubation phase, its influence on nitrate leaching was more complex and time dependent. This divergence highlights the importance of optimizing biochar application rates to balance ammonium retention and nitrate mobility in coarse-textured soils.

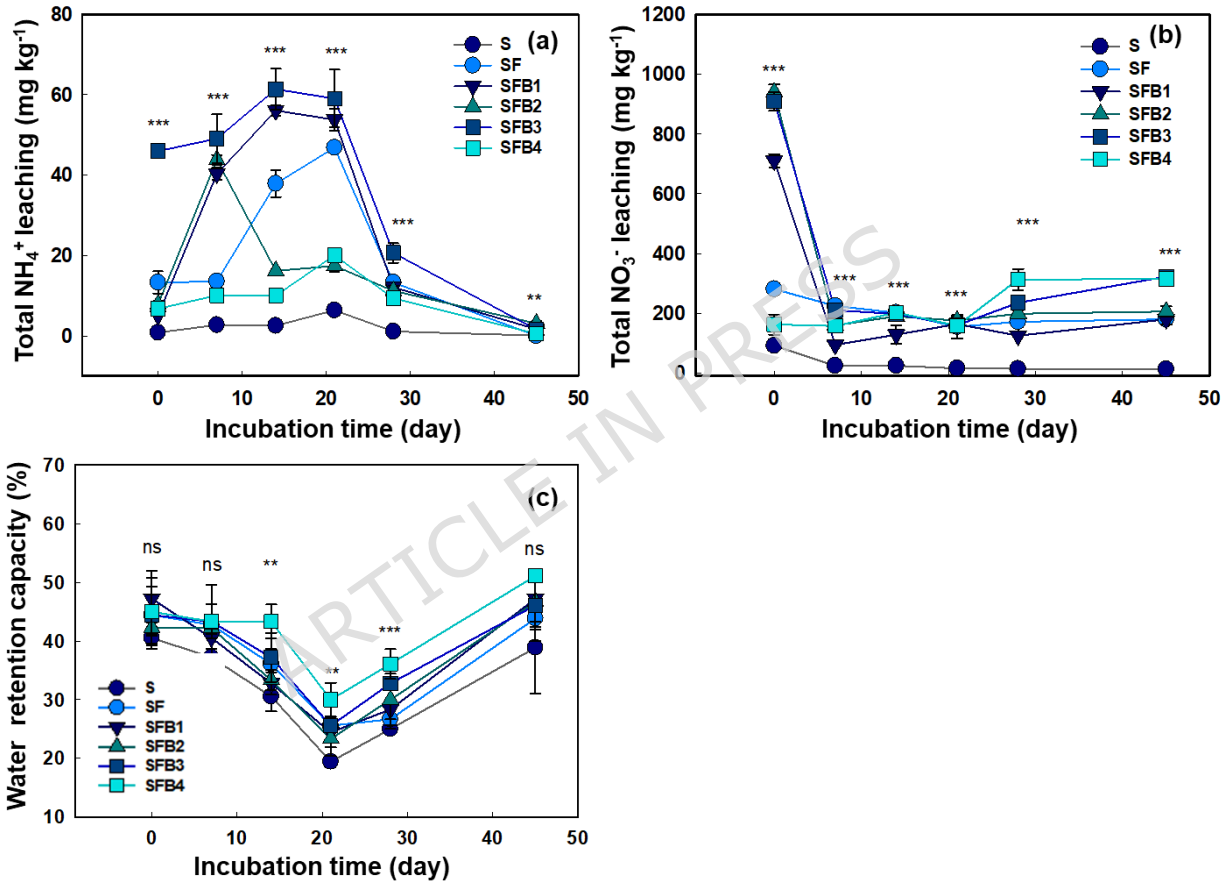


Fig. 4. Cumulative (a) ammonium (NH_4^+) and (b) nitrate (NO_3^-) leaching profiles, alongside (c) soil water retention capacity as influenced by corncob biochar application over the incubation timeline.

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*, **, and *** differ significantly at 0.05, 0.01, and 0.001, respectively. Different letters indicate statistically significant differences (p<0.05, LSD), while the same letter suggests no significant difference between treatments.

3.5 Biochar-induced changes in soil water retention

Sandy soil, characterized by larger particles and increased pore space, has a greater infiltration rate, which greatly influences the mobilization of reactive nitrogen. Therefore, it is essential to comprehend the interaction relationship between compaction, soil type, and moisture on nitrogen dynamics [42]. Consequently, assessing the impact of soil amendments on water retention and movement is crucial for elucidating nitrogen transport and reducing nutrient losses in coarse-textured soil. To evaluate the role of corncob biochar in regulating soil moisture conditions, soil water retention capacity was monitored throughout the incubation period (Fig. 4c). During the initial incubation phase (0-7 days), all treatments exhibited comparable water retention capacities (approximately 40-50%), with no statistically significant differences among treatments ($p > 0.05$). This indicates that short-term moisture retention was primarily governed by inherent soil texture rather than biochar amendment. However, pronounced treatment-specific differences emerged as incubation progressed. By day 21, all treatments showed a marked decline in water retention capacity, reflecting moisture stress conditions; nevertheless, biochar-amended soils maintained significantly higher water retention than the control and fertilizer-only treatments. Among the biochar treatments, SFB4 consistently exhibited the highest water retention capacity throughout the stress period, remaining above 30% at day 28, whereas the control treatment declined below this threshold. At the end of the incubation period (day 45), SFB4 achieved the highest water retention (51.11%), followed by SFB1, SFB2, and SFB3, while the SF and S treatments showed substantially lower values. These results demonstrate a clear rate-dependent

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effect of corncob biochar on soil water retention, with higher application rates providing greater resistance to moisture loss. Importantly, the observed improvement in water retention capacity under biochar amendment represents a key mechanistic link between soil physical properties and nitrogen leaching behavior. Enhanced moisture retention under SFB3 and SFB4 likely prolonged water residence time and altered solute transport pathways, thereby influencing the contrasting leaching patterns of NH_4^+ and NO_3^- observed in Fig. 4(a–b). This depth- and rate-dependent hydrological modification provides novel evidence that biochar-mediated changes in soil water status play a critical role in regulating nitrogen mobility in sandy loam soils. Overall, this study demonstrates that corncob-derived biochar not only improves soil water retention under moisture stress conditions but also indirectly controls nitrogen leaching dynamics by modifying soil hydrological behavior. The pronounced and persistent effect observed at higher biochar application rates highlights the importance of optimizing biochar dosage to simultaneously enhance water retention and mitigate nutrient losses in coarse-textured agricultural soils.

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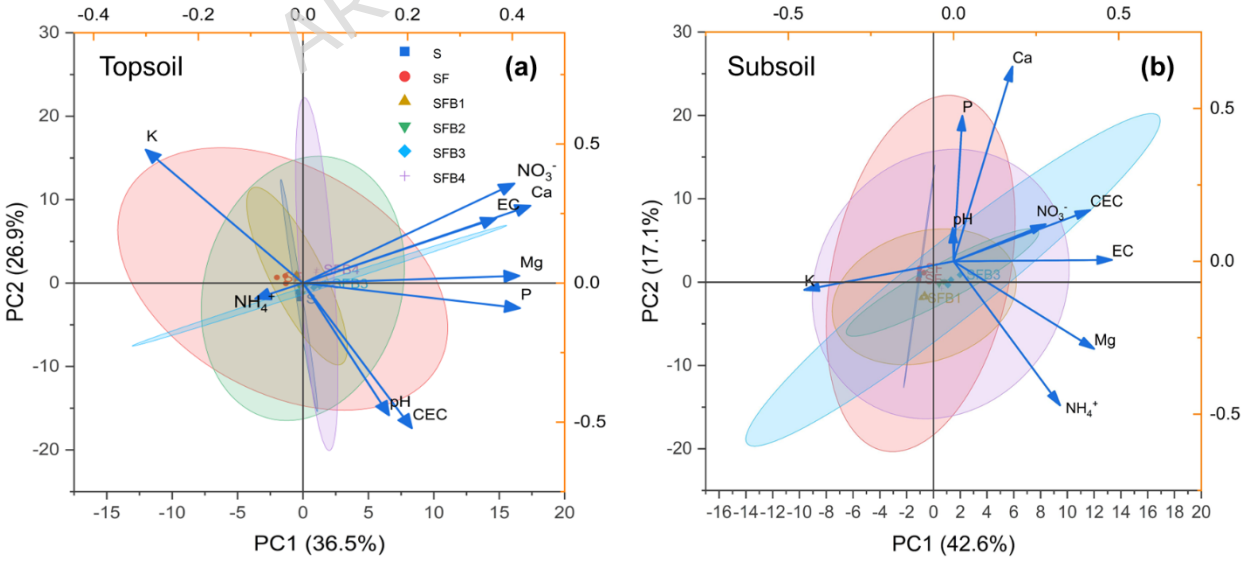
3.6 Multivariate relationships between soil properties and nitrogen leaching

To elucidate the relationships between corncob biochar application, soil physicochemical properties, and nitrogen leaching in sandy loam soil, PCA was performed for both topsoil and subsoil layers (Fig. 5a-b). In the topsoil, the first two principal components explained 63.4% of the total variance, with PC1 and PC2 accounting for 36.5% and 26.9%, respectively (Fig. 5a). Clear separation among treatments was observed along PC1, indicating that biochar amendment substantially altered soil properties and nitrogen leaching behavior relative to the control and fertilizer-only treatments. In the topsoil, soil EC, exchangeable Ca and Mg, and NO_3^- leaching loaded positively along PC1 and were closely associated with higher biochar application rates (SFB3 and SFB4). In contrast, NH_4^+ leaching showed an opposite loading direction, indicating an

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inverse relationship with these soil parameters. This pattern suggests that biochar-induced increases in ionic strength and base cation availability were associated with enhanced nitrate mobility, while ammonium retention was promoted under the same conditions. In the subsoil, the first two principal components explained 59.7% of the total variance, with PC1 accounting for 42.6% and PC2 for 17.1% (Fig. 5b). Treatments amended with biochar (SFB2-SFB4) were clearly separated from the control and fertilizer-only treatments along PC1. Positive loadings of pH, available P, Ca, CEC, and EC were strongly associated with NO_3^- leaching in these treatments, indicating that biochar-driven improvements in subsoil chemical properties influenced nitrate transport. Conversely, NH_4^+ leaching exhibited a negative association with Mg, suggesting enhanced ammonium retention through cation exchange processes in the subsoil. Overall, the PCA results highlight depth-dependent controls on N mobility in sandy loam soil. While NO_3^- leaching was primarily associated with biochar-induced changes in soil chemical properties and ionic composition, NH_4^+ retention was governed by cation exchange-related mechanisms, particularly at higher biochar application rates.

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Fig. 5. PCA depicting the multivariate relationships among soil physicochemical properties and $NH_4^+$and NO_3^- leaching behavior in the (a) topsoil and (b) subsoil.

4. Discussion

4.1 Modulation of soil nutrient dynamics by biochar amendment

Soil nutrient status is a critical indicator for evaluating the effectiveness of biochar in practical soil management applications [43]. Among soil properties, pH plays a pivotal role in regulating nutrient availability, microbial activity, and overall soil fertility, and is widely recognized as a key determinant of soil chemical behavior [40]. In the present study, the application of corncob biochar resulted in a pronounced increase in soil pH, with values rising from 6.04 in the unamended sandy loam soil to 7.57-7.72 in the topsoil and 7.97-8.07 in the subsoil, depending on the application rate.

Notably, corncob biochar applied at 2% and 3% (SFB2 and SFB3) induced higher soil pH values compared with the 1% and 4% treatments (SFB1 and SFB4), suggesting that moderate application rates are more effective in enhancing soil alkalinity. This response can be attributed to the substantial presence of alkaline ash constituents and base cations (K^+, Ca^{2+}, and Mg^{2+}) in the produced corncob biochar, which neutralize soil acidity through cation exchange and carbonate-associated reactions. However, soil pH in the biochar-amended treatments did not differ significantly from that in the fertilized soil (SF) for both topsoil and subsoil, indicating that corncob biochar can achieve pH adjustment comparable to conventional fertilization practices while potentially offering additional soil health benefits.

Biochar has been shown to increase soil pH in sandy loam soils, which may contribute to improved nutrient retention and soil fertility [44]. In terms of soil pH modification, corncob biochar application significantly enhanced soil CEC and available P concentrations. The increase

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in CEC was particularly evident in the 2% and 3% biochar treatments, which corresponded closely with the observed elevation in soil pH. This relationship highlights the role of biochar-induced alkalization in increasing the density of negatively charged functional groups on biochar surfaces, thereby improving the soil's capacity to retain exchangeable nutrient cations. Enhanced CEC is especially important in sandy loam soils, which are inherently characterized by low nutrient-holding capacity and high susceptibility to nutrient leaching.

Biochar application at rates of 2-3% (w/w) markedly increased the availability of essential nutrients, including P, K^+, Ca^{2+}, and Mg^{2+} (Table 2). This improvement can be attributed to both the intrinsic nutrient content of corncob biochar and its strong nutrient-retention capability, which limits nutrient losses and promotes their gradual release into the soil solution [45]. The microporous structure of corncob biochar, as revealed in Fig. 1(b), provides abundant adsorption sites for NH_4^+ and NO_3^- ions, thereby enhancing nitrogen retention and reducing the risk of leaching losses. Such physical entrapment, combined with electrostatic interactions [46], plays a key role in stabilizing inorganic nitrogen forms in coarse-textured soils.

Moreover, the well-developed porous architecture of the produced biochar contributes to improved soil water retention capacity, as evidenced by the higher water-holding capacity observed in biochar-amended soils (Fig. 4(c)). Improved water retention not only benefits plant water availability but also indirectly enhances nutrient retention by reducing percolation-driven nutrient losses. Collectively, these findings demonstrate that corncob biochar, particularly at moderate application rates (2-3%), effectively improves soil nutrient availability and retention through synergistic chemical and physical mechanisms, underscoring its potential as a sustainable soil amendment for nutrient-poor sandy loam soils.

4.2 Roles of corncob biochar in mediating water retention

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The utilization of biochar to improve soil water retention has garnered significant global interest [47]. The use of biochar may enhance soil physical characteristics and increase water retention capacity owing to its significant porosity and extensive specific surface area [30]. The result demonstrated that the incorporation of corncob biochar amendments (denoted by treatments SFB1 to SFB4) markedly affected the soil's water retention capacity during the incubation period, as seen in Fig. 4(c). All biochar-treated soils exhibited an improved capacity for water retention relative to the unamended soil (S) and the SF treatment, especially evident on days 21 and 28 of incubation. The most significant benefit was noted with SFB4, which continuously exhibited superior water retention during the incubation period, indicating that this treatment enhances the structural and hydrophysical features of the soil matrix.

This improvement is due to the porous structure and elevated specific surface area of corncob biochar, which promotes increased water adsorption and retention in soil aggregates [47]. Enhanced water retention is likely attributable to the augmented organic matter and superior aggregation linked to biochar inclusion, which diminishes evaporation and percolation losses. The transient decrease in water retention around day 21 for all treatments likely indicates microbial activity or decomposition dynamics that temporarily modify soil porosity, subsequently followed by recovery owing to stabilizing mechanisms.

A reasonable explanation would elucidate this phenomenon. The hydrophilic soil transitioned to hydrophobic following biochar amendment due to its hydrophobic aliphatic carbon composition. Reports indicate that oxidizing the surface of biochar improves the quantity of acidic functional groups, resulting in increased hydrophilicity thereby enhancing water absorption and retention [48]. It has been suggested that incorporating biochar into sandy soil may diminish the water penetration rate by decreasing large soil pores and enhancing stable aggregates [49]. Recent

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investigations have shown that the particle size of a biochar significantly influences its efficacy. Smaller biochar particles can occupy larger soil pores, resulting in a more complex pore network that improves water retention. The previous study discovered that incorporating tiny biochar particles into coarse sandy subsurface markedly enhanced water retention and influenced hydraulic conductivity [50]. Furthermore, the feedstock and pyrolysis parameters employed in biochar production affect its characteristics and, therefore, its effect on soil water dynamics [51]. A carbon-based material exhibited significant water absorption capacity and noted its beneficial impact on the water retention properties of sandy soil [52]. A meta-analysis conducted by previous study indicated that the efficacy of biochar in enhancing soil water retention is contingent upon soil texture, with coarse-textured soils deriving the greatest advantage. This indicates that the utilization of corncob biochar may be especially advantageous in sandy soils, which are common in specific areas [50]. Moreover, biochar's function in augmenting soil aggregation enhances water retention. The development of stable soil aggregates enhances pore connectivity and water retention capacity. Biochar alters soil physical qualities mostly via affecting soil structure rather than its internal porosity [53].

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4.3 Leachate properties and N retention

The NO_3^- leaching constitutes the principal avenue of N loss in intensive greenhouse vegetable growing. A meta-analysis of NO_3^- leakage from synthetic and organic fertilizers was conducted over the previous four decades. The results indicate that both fertilizer types substantially contributed to nitrate losses, with greater susceptibility observed in light-textured soils such as sandy loam due to their high permeability and limited nutrient retention capacity [52]. In contrast, biochar amendments have been shown to significantly influence nitrogen retention and loss dynamics by improving soil nutrient-holding capacity and reducing nitrogen leaching in

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agricultural lands, resulting in considerable groundwater nitrogen contamination. In our experiment, the produced corncob biochar did significantly affect the leaching of NH_4^+ and NO_3^-. The use of biochar along with nitrogen fertilizer resulted in increased leaching of NH_4^+ and NO_3^- relative to the absence of biochar in sandy loam soil. Conversely, a contrasting trend was seen in the preservation of NH_4^+ and NO_3^- in topsoil and subsoil at the end of the experiment. The retention of NH_4^+ in the topsoil was considerably higher in the treatment including fertilizer combined with 3% corncob biochar compared to soil treated with fertilizer alone. However, the other biochar treatments at 1%, 2%, and 4% did not exhibit significant the retention of NH_4^+ differences compared to the control group. Clear evidence of NH_4^+retention in the subsoil was seen across four treatments using corncob biochar application, with the maximum retention in SFB1 and SFB3, followed by SFB2 and SFB4, respectively. While the soil alone and soil with fertilizer exhibited the considerably lowest NH_4^+ retention in the subsoil.

The retention of NO_3^- in the topsoil was greatest with the application of corncob biochar at 4%, 3%, and 1% concentrations, respectively. The corncob biochar incorporation at 2% did not yield a statistically significant difference compared to soil with fertilizer and soil alone. The greatest retention of NO_3^- in subsoil was noted in the treatment with 4% corncob biochar application. The empirical data indicated that elevated biochar application (3-4%) markedly improves water and NH_4^+ retention yet may exacerbate NO_3^- leaching. Nonetheless, the application of lower corncob biochar (2% and 3%) did not exhibit a statistically significant change compared to the soil treatment with fertilizer (SF). However, the soil only (control group) was classified as the lowest in NO_3^- retention inside the subsoil.

The quantity of corncob biochar applied influenced the overall NH_4^+ and NO_3^- leaching. Excessive application of biochar has resulted in significant leaching losses of NH_4^+ and NO_3^- in

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both the topsoil and subsoil. However, we discovered that corncob biochar-treated sandy loam soil exhibited increased retention of NH_4^+ and NO_3^- with elevated leaching of these ions. This may appear paradoxical however, it may be elucidated by the distinct properties of both biochar and sandy soil, together with the behavior of NH_4^+ and NO_3^- in both systems. Biochar's elevated CEC improves NH_4^+ retention in sandy soils by cation adsorption nevertheless, its anionic surface functional groups (e.g., carboxylate) are ineffective in retaining NO_3^-. This leads to reduced NH_4^+ leaching but heightened NO_3^- leaching over time, particularly in soils with poor native CEC, such as sandy soils [54]. In sandy soils enhanced with 2-4% biochar, NH_4^+ leaching diminished by 48.5-66.7%, however NO_3^- leaching escalated by 22.6% due to restricted anion retention capacity [54]. The alkaline properties of corncob biochar can enhance nitrification (the transformation of NH_4^+ and NO_3^-) in sandy soils, hence increasing the availability of NO_3^- for leaching, despite the initial retention of NH_4^+. This issue is intensified in soils with inadequate water retention, where biochar may temporarily store nutrients but cannot avert leaching under heavy irrigation or rainfall. Although biochar's porosity and CEC improve short-term NH_4^+ retention, the inadequate water-holding ability of sandy soils restricts prolonged nutrient storage [55]. Under conditions of intense precipitation or irrigation, NO_3^- produced by nitrification is swiftly leached. Research indicates that sandy soils supplemented with biochar have 30-40% elevated NO_3^- concentrations in leachate during simulated rainfall events relative to unamended soils. While small reductions (up to about 36%) in NO_3^- leaching with certain high-microporosity biochars but underscored that the effect is significantly contingent on feedstock and texture [14]. Despite biochar's often restricted direct adsorption capacity for negatively charged NO_3^- ions owing to its surface charge, it may still sequester nitrate via trapping within its porous architecture and stability within organo-mineral coatings on biochar particles. This can temporarily sequester NO_3^- in the soil [57].

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Even though the current investigation showed higher NH_4^+ and NO_3^- concentrations in several biochar-amended treatments, these increases shouldn't be taken exclusively as proof of physicochemical nitrogen retention. The synthesis and distribution of inorganic nitrogen in soil may also be impacted by biochar's influence on nitrogen transformation processes, such as urea hydrolysis, ammonification, and nitrification. The relative contributions of nitrogen transformation processes and physicochemical retention mechanisms could not be clearly differentiated in this investigation since nitrogen mineralization and urea retention were not directly measured. To understand the underlying mechanisms, future research should include direct measurements of nitrogen transformation processes. As a result, the reported nitrogen dynamics should be interpreted cautiously

4.4. Relationship of biochar treated with the nutrient leachate

The PCA biplots were used to elucidate the multidimensional relationships between corncob biochar application rates and nutrient leaching dynamics particularly NH_4^+ and NO_3^-. In the topsoil, the first two principal components (PC1 and PC2) accounted for accounted for 36.5% and 26.9%, respectively, effectively segregating treatments based on their physicochemical impact (Fig. 5a). The biplot reveals that higher biochar application rates (3% and 4%; SFB3 and SFB4) clustered along the positive axis of PC1, showing strong positive loading with soil EC and exchangeable Ca and Mg. Interestingly, these treatments displayed a close vectorial association with NO_3^- leaching. This suggests that while corncob biochar significantly enriches the soil with essential cations, the concomitant increase in ionic strength and potential competition for anion exchange sites may inadvertently facilitate NO_3^- mobility under specific conditions. Conversely, NH_4^+ leaching exhibited an orthogonal or negative correlation with the primary soil fertility parameters (CEC, Ca, and Mg). This negative loading indicates that the enhancement of soil CEC

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and the abundance of oxygen-containing functional groups-facilitated by corncob biochar amendment-effectively promoted NH_4^+ retention through electrostatic attraction and cation exchange [43]. Biochar's inherently negative surface charge, attributed to surface oxygen-containing functional groups, provides abundant adsorption sites that preferentially bind NH_4^+ (a cation), thereby limiting its mobility and reducing leaching losses. In contrast, NO_3^-, being an anion, is less strongly bound and remains more labile in the soil solution, consistent with findings in sandy-textured soils where biochar amendments have been shown to reduce mineral N leaching primarily through enhanced NH_4^+ retention [45].

For the subsoil dataset, PCA revealed that PC1 and PC2 accounted for 42.6% and 17.1% of the total variance, respectively (Fig. 5b). Treatments SFB2, SFB3, and SFB4 showed strong positive associations with available phosphorus, pH, CEC, and EC, which were also positively correlated with NO_3^- leachate. This suggests that higher biochar application rates in the subsurface layer influence nitrogen transformation and mobilization dynamics, potentially through altered soil physicochemical properties and microbial processes that regulate nitrification and nitrogen movement through the profile. Enhanced soil pH and CEC associated with biochar amendment can shift the balance of N processes by increasing nitrifier activity or substrate availability for nitrification, ultimately affecting NO_3^-formation and transport in coarse-textured soils. Recent studies confirm that biochar–fertilizer interactions improve nitrogen retention and reduce overall inorganic N leaching relative to fertilizer alone, highlighting improved nutrient capture and moderated N transformation rates under biochar-enhanced conditions [45], [57].

Conversely, NH_4^+ leachate exhibited a strong inverse correlation with subsurface Mg concentrations, implying that Mg availability-possibly influencing cation exchange dynamics or pH-dependent adsorption processes-may enhance NH_4^+ retention in deeper soil layers. The

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elevated CEC and altered surface properties of biochar-amended soils create additional adsorption and exchange sites that preferentially bind NH_4^+, reducing its mobility relative to NO_3^-. This pattern is consistent with previous findings that co-application of biochar with nitrogen fertilizer can significantly reduce inorganic N leaching and improve nitrogen use efficiency compared to nitrogen fertilizer alone; for example, biochar-based nitrogen fertilizer treatments reduced inorganic N leaching by an average of ~35% relative to conventional nitrogen fertilizer in vegetable soils, indicating enhanced NH_4^+ retention and moderated nitrification losses [58]. Taken together, the PCA results and recent literature support the interpretation that corncob biochar amendment at moderate to high rates (e.g., SFB3-SFB4) not only alters soil chemical properties (pH, CEC, EC) but also modulates nitrogen transformation pathways in subsurface soil-enhancing NH_4^+ retention while influencing NO_3^-dynamics through interactions with soil nutrient carriers and hydrological processes.

Despite the current study employing three biological replicates per treatment, a standard replication level for controlled soil incubation studies, the limited sample size may constrain the validity of multivariate analysis, such as PCA. The PCA results should be regarded largely as exploratory evidence of the links between soil characteristics and nitrogen dynamics. Future studies with larger sample sizes and field-scale validation are recommended to further confirm these relationships.

5. Conclusions

This study provides a comprehensive assessment of the synergistic effects of corncob-derived biochar and nitrogen fertilizer on N dynamics within a sandy loam soil profile. Our findings demonstrate that biochar amendment fundamentally reconfigures the soil's physicochemical matrix-specifically pH, CEC, and hydraulic properties-thereby dictating the mobility and retention

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of inorganic N species (NH_4^+ and NO_3^-). A pivotal finding of this research is the rate-dependent divergence in nitrogen retention mechanisms. While a moderate application rate (3% w/w) optimized NH_4^+ stabilization through enhanced electrostatic attraction and CEC, higher application rates (4% w/w) prioritized soil hydrological improvements and water-holding capacity. However, the study reveals a critical threshold: increasing biochar dosages did not linearly correspond to reduced NO_3^- losses. This suggests that the anionic repulsion between the biochar's oxygen-containing functional groups and NO_3^- ions may offset the benefits of improved physical water retention, particularly in coarse-textured soils. Furthermore, the depth-resolved analysis employed here highlights that N-leaching is not merely a surface phenomenon; subsoil processes play a decisive role in the long-term fate of fertilizers. The multivariate PCA confirmed that NH_4^+ and NO_3^- are governed by distinct, non-overlapping retention pathways, necessitating a more nuanced approach to soil amendment. In conclusion, corncob biochar serves as a potent tool for enhancing nitrogen use efficiency and soil moisture status. However, we emphasize that application rates must be strategically optimized to balance the stabilization of ammonium against the potential mobilization of nitrate. These insights are vital for developing site-specific fertilizer management practices that aim to mitigate groundwater contamination and enhance the sustainability of vulnerable agricultural systems.

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Data availability

Data will be made available on request.

Declaration of competing interest

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

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