Scientific Reports

https://doi.org/10.1038/s41598-026-53870-0

Article in Press

Evaluating biochar's potential to reduce nitrate leaching and enhance wheat (*Triticum aestivum* L.) yield under different nitrogen management practices

Received: 2 January 2026

Accepted: 14 May 2026

Published online: 22 May 2026

Cite this article as: ul Haq M., Khan Z., Nawaz A. *et al.* Evaluating biochar's potential to reduce nitrate leaching and enhance wheat (*Triticum aestivum* L.) yield under different nitrogen management practices. *Sci Rep* (2026). https://doi.org/10.1038/s41598-026-53870-0

Mauz ul Haq, Zaryab Khan, Aman Nawaz & Abd Al Karim Jaafar

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

ARTICLE IN PRESS

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

Evaluating Biochar’s Potential to Reduce Nitrate Leaching and Enhance Wheat (Triticum aestivum L.) Yield Under Different Nitrogen Management Practices

Mauz ul haq[1], Zaryab Khan[1**], Aman Nawaz[1], Abd Al Karim Jaafar[2,3*]

[1]Department of Soil and Environmental Sciences, The University of Agriculture Peshawar. muazk240@gmail.com (M.U); soilscience810@gmail.com (A.N); (Khan.zaryab1986@gmail.com (Z.K).
[2]Department of Soil Science, College of Agricultural Engineering, Damascus University, Damascus, Syria. a.karimjaafar@gmail.com;abdalkarim.jaafar@damascusuniversity.edu.sy
https://orcid.org/0000-0003-3071-1850
[3]Soil Science Society of Syria [SSSS], Damascus, Syria
Corresponding author: Abd Al Karim Jaafar; Zaryab khan

ABSTRACT

Nitrate (NO_3^-) leaching from alkaline coarse-textured agricultural soils is a major concern that reduces nitrogen use efficiency (NUE) and limits crop productivity. Application of biochar has been found to improve soil fertility through nutrient retention when used with nitrogen fertilizer, however, its efficacy in coarse-textured alkaline soil is insufficiently explored. A greenhouse pot experiment was carried out comprising completely randomized design (CRD) with five treatments and three replicates (15 pots) to investigate the effects of biochar applied with N doses on NO_3^- leaching, N uptake and wheat yield. The treatments consisted of T1 (Control), T2 (Nitrogen 75 kg ha^{-1}), T3 (Nitrogen 150 kg ha^{-1}), T4 (2% biochar + Nitrogen 75 kg ha^{-1}), and T5 (2% biochar + Nitrogen 150kg ha^{-1}). Biochar application had significantly reduced NO_3^- leaching compared to no biochar with T4 and T5 showing the lowest levels of NO_3^- losses. All the biochar applied treatments produced high grain yield, N uptake, and improved NUE in terms of treatments with no biochar applied. The decrease in NO_3^- leaching was coupled with increased N retention in the soil and enhanced plant growth parameters. This research indicates that 2% biochar with 150 kg N ha^{-1} is the most effective treatment to ensure maximum wheat production and reduces NO_3^-- leaching in alkaline coarse-textured soils.

Keywords: Sustainable Agriculture, Nutrient Retention, Soil Fertility, Crop Production

Introduction

Nitrogen losses in the soil-plant system not only diminish soil fertility and crop yield but they can also negatively impact the environment [1]. However, when the supply of N surpasses crop demand, environmental contamination results [2]. The mineral N in the soil is easily removed by crops, immobilized, and lost to the environment by volatilization, surface runoff, and leaching[3]. Compared to NH_4^+ in alkaline, dry, and semiarid environments, soil native charged colloids are predominantly negatively charged. These colloids hinder nitrate (NO_3^-) from absorbing on their surfaces. This phenomenon accelerates the downward movement of NO_3^- along with drainage water, leading to its rapid leaching into the soil [4].

The application of N fertilizer has exceeded its optimal levels. Due to its solubility, nitrate has a mobilized nature and potential for soil loss due to leaching [5]. Croplands subjected to substantial agricultural practices emerge as the predominant origin of leached nitrogen (NO_3^-) in the environment [6]. NO_3^--N leaching is found to be profoundly impacted by the composition of the soil and prevailing climatic conditions. A notable instance of this phenomenon was observed in sandy soil, where an application of 87 kg N ha^{-1} led to substantial NO_3^- leaching, as opposed to the 10 kg N ha^{-1} observed in loamy soils [7].

Wheat (*Triticum aestivum L.*), a globally important cereal crop and staple food source, has a high N demand making it particularly vulnerable to N losses through leaching in sandy soils[8 9]. Thus, optimization of N use and loss reduction in wheat-based systems is essential to attain sustainable agricultural production, especially in areas where alkaline sandy loam soils predominate.

The process of NO_3^- leaching can be mitigated through various management practices, including optimized N application timing, cover cropping, and the use of soil amendments. Among these, the application of biochar has recently garnered increased interest due to its dual benefits of mitigating climate change and enhancing soil quality [10]. Biochar is a carbon-rich solid produced by pyrolysis of biomass under limited oxygen conditions[11]. This organic source has been demonstrated to reduce nitrogen leaching through the enhancement of the soil's cation exchange capacity (CEC) and anion exchange capacity (AEC) [12].

Despite extensive research on biochar for soil fertility and nutrient retention, its effect on NO_3^- leaching in coarse-textured alkaline soils remains insufficiently investigated. Furthermore, the interaction between biochar and N application under controlled conditions that isolate N dynamics has received little attention, leaving key mechanisms poorly understood. Consequently, the processes through which biochar affects the retention of N and the provision of N to plants in such soils are not well established.

The role of biochar in improving N retention in alkaline sandy loam soils is a promising strategy in enhancing the efficiency of N use and reducing environmental losses in cereal-based production systems. Therefore, Controlled greenhouse pot experiment was thus required as a pilot study to show the potential of biochar as a nitrogen retaining amendment before the more complex field-scale studies were undertaken.

Our hypothesis was that the application of biochar in alkaline sandy loam soil would decrease NO_3^- leaching and enhance the retention of soil N, thus optimizing the growth and yield of wheat under N-fertilized conditions. With this hypothesis our objectives were : (1) to quantify biochar effect on NO_3^- leaching and (2) to determine its impact on post-harvest soil and plant N concentrations, total N uptake and wheat yield in a controlled greenhouse experiment . The novelty of this research lies in its focus on alkaline sandy loam soil — a coarse textural class characterized by inherently low nutrient retention and less N availability to plants . Addressing this knowledge gap is essential for developing sustainable N management strategies in these soils, where fertilizer losses are high and crop productivity is often limited.

Materials and methods

Description of the experiment

Random soil samples were collected using auger from a depth of 0–20 centimeters at the Agricultural Research Farm of the University of Agriculture, Peshawar. After air-drying, the debris was subjected to a sieving process utilizing a 2-mm filter. A sand:soil mixture (2:1, w/w) was made to simulate a coarse-textured soil with high potential for NO_3^- leaching. This practice was specifically aimed at increasing microporosity and hydraulic conductivity in controlled environments to produce a leaching-prone environment to be used in assessing N dynamics. The experiment was performed in plastic pots with a 12 inches diameter (30 cm height x 30.5 cm diameter) filled with 10 kg of the prepared sand soil mixture (2:1). The bulk density of the soil was set to 1.42 g cm^{-3}. Soil sample from the top 10 cm in the pots were thoroughly mixed with N and biochar levels. The pots were marked at two distinct heights, corresponding to soil depths of 10 cm and 20 cm, respectively. All pots were thoroughly hydrated with 1 liter of water. Ten wheat seeds were planted in each pot, and the five most vigorous plants were selected for further study. Leachate samples were collected at 14, 24, 34 and 74 days after sowing (DAS). The first three leachate samples were collected at 10-day intervals to monitor early N leaching, while the final sample was collected at 74 DAS to evaluate late-season leaching as the crop matured. Each pot was saturated with 200 ml of distilled water 24 hours prior to leachate collection. Leachate collected from all the pots was further analyzed to ascertain its pH, electrical conductivity (EC), mineral nitrogen (MN), and nitrate nitrogen (NO_3^--N) concentrations. Subsequent to the harvesting, soil samples were collected from the pots at depths of 10 centimeters and 20 centimeters for analyzing various parameters, including pH, electrical conductivity (EC), and NO_3^--N.

Physico-chemical Properties of the Soil

The soil is characterized by a textural class of sandy loam, comprising 56.5% sand, 34.1% silt, and 9.4% clay. The pH of 8.1 indicates that the soil is significantly alkaline, exhibiting an EC of 0.17 dSm^{-1}. This soil had relatively lower levels of organic matter (0.36%) and moderate N content (0.049%).

Irrigation levels and water management

Water holding capacity was determined as 23.6 ± 1.8%(v/v) indicating the coarse texture of the growth medium. Irrigation was done in a measured volumetric method with distilled water to ensure uniformity in the soil moisture content across treatments. Water was added manually using a graduated cylinder. Each pot was given 1 L of water at sowing. During the growth phase, 250 mL of water was added after every three days, maintaining approximately 50-60% of WHC to mimic moderate conditions of moisture and avoid water stress. Furthermore, 200 mL of water was given to all the pots 24 hours prior to leachate collections (14, 24, 34 and 74 DAS) to ensure the consistency in percolation and measurable amounts of leachates. The amount of leachate collected was measured at every collection point, and subsamples were tested to determine the concentration of NO_3^--N.

Biochar used for the experiment

The biochar used in this experiment was derived from mixed hardwood feedstock (primarily sheesham and poplar) in the form of wood ash. It was produced using “on farm” method by slow pyrolysis at 550 °C over 2 hours under limited oxygen conditions, as has been done under the conventional biochar production protocols using woody biomass [13]. The process consists of two cylindrical cores (drums), one external to produce heat and other internal where feedstock is placed to produce biochar through pyrolysis. The biochar was prepared and used after being sieved to a particle size of less than 2 mm, [14]. Table 1 summarizes some of the important physicochemical characteristics of the hardwood biochar.

Table 1. Physiochemical characteristics of the hardwood biochar

Properties	Unit	Concentration
Feedstock	–	Mixed hardwood
Pyrolysis temperature	°C	550
pH (1:20 biochar:water)	–	10.2
Electrical Conductivity (EC)	dS m^{-1}	3.5
Ash content	%	25.8
Total carbon (C)	%	58.6
Total nitrogen (N)	%	0.9
Cation Exchange Capacity (CEC)	$\text{cmol}_{+}\ \text{kg}^{-1}$	32.1
Anion Exchange Capacity (AEC)	$\text{cmol}_{-}\ \text{kg}^{-1}$	5.3
Porosity	%	48

A biochar application (2% w/w) was chosen in regard to past research that has indicated that low to moderate levels of biochar (1-3%) are effective in enhancing nutrient retention and reducing nitrate leaching in sandy-to-sandy loam soils, without having excessive effects on soil pH or salinity [15]. Since the experimental soil was alkaline (pH 8.1), it was purposely avoided to raise the biochar rates to prevent the possible negative impact on the availability of the nutrients.

NO_3^--N losses

In order to measure the total amount of nitrogen loss through leaching during the wheat growing period, cumulative nitrate-nitrogen (NO_3^--N) loss was estimated in each pot using following formula.

$$NO_3^- \text{-N loss} (\text{mg pot}^{-1}) = C \times V$$

$$NO_3^- \text{-N loss} (\text{mg pot}^{-1}) = \sum_{i=1}^{4} (ci \times vi)$$

C= concentration of NO_3^--N (mg L^{-1}) , V= Volume of Leachate (L) i= leachate collection events i.e. 1,2 3, and 4. The volume of collected leachate was measured at four leaching events (14 DAS, 24 DAS, 34 DAS, and 74 DAS), and a subsample was analyzed for NO_3^--N concentration (mg L^{-1})

Physio chemical attributes of the soil

The soil pH and EC were determined in a 1:5 soil suspension. 10 g of soil were stirred in a conical flask with 50 milliliters of water for 25 minutes. Then, the pH and EC were determined using a pH meter and an EC meter, respectively, according to the methods proposed by McLean (1983)[16] and Richards. (1954) [17]. To determine the soil texture, a 50 g sample of soil was blended with 10 ml of Na_2CO_3 in a dispersion machine for five minutes. Hydrometer measurements were taken after 40 seconds and two hours [18].

The procedure established byNelson and Sommers (1982)[19] was used to calculate the amount of organic matter in the soil. Ten milliliters of 0.5 N potassium dichromate and 20 milliliters of concentrated sulfuric acid (H_2SO_4) were combined with 1 g of soil. The mixture was allowed to cool for around 30 minutes. After cooling, 200 mL of distilled water was added, and the liquid was filtered. The filtrate was titrated against 0.5 N ferrous sulfate ($FeSO_4$) in the presence of two to three drops of ortho phenolphthalein indicator until a color shift occurred. The given formula was used to compute the organic matter content.

$$\% \text{ SOM} = \frac{[(\text{ml of } K_2Cr_2O_7 \text{-ml of Fe } (NH_4)\ SO_4)] \ \times\ 0.69}{\text{Weight of soil (g)}}$$

Mineral Nitrogen in Soil

Mineral nitrogen (MN) was determined using a KCl solution and identified using Keeney et al. (1983) [20] steam distillation technique. MN was found to be in the forms of NH_4^+-N and NO_3^--N. Using this approach, 20 grams of soil from each pot after harvest were agitated for one hour with 100 milliliters of 1 M KCl solution. Then, the soil was filtered through Whatman-42. To analyze NH_4^+-N or NO_3^--N, 20 mL of the filtrate was distilled using MgO or MgO + Devardas alloy. In all cases, the N was collected in a 5-ml solution of mixed indicators and boric acid until the level reached 75 ml. Then, it was titrated against 0.005 N HCl until a pink color appeared. 70 µg N mL^{-1} corresponded to one milliliter of 0.005 N HCl. The NO_3^--N concentration was determined by subtracting the NH_4^+ concentration from the NO_3^-+NH_4^+ concentration.

$$\text{Min.N (mg kg}^{-1}\text{)} = \frac{\text{(Sample -Blank reading)} \times \text{meq.N} \times \text{N of HCL} \times \text{Volume KCl} \times 10}{\text{Weigh of sample} \times \text{Volume for distillation}}$$

Post harvest Analysis

Total Nitrogen in Plant

To appraise the nitrogen content of the plant, the Kjeldhal approach was utilized, as suggested by Bremner et al. (1983) [21]. 0.2 g of pulverized leaf and stem mixed plant material was placed within the digestion tubes. Then, 1.1 g of the digestion mixture was added. This mixture was a 100:10:1 combination of $K_2Cr_2O_7$, $CuSO_4$, and Se. After adding 3 cc of H_2SO_4, the tubes were placed in a block digester and allowed to digest for three hours at 450°C.Twenty milliliters of the absorb solution were distilled using a five-milliliter boric acid mixed indicator containing two indicators: methyl red and bromochresol green. Then, the distillate was titrated against 0.005 M HCl to measure NH_4^+. The following formulas was used

$$\text{Total N (\%)} = \frac{\text{(Sample-Blank)} \times 0.005 \times 0.014 \times 100 \times 100}{\text{(wt of Sample} \times \text{Volume taken for distillation)}}$$

$$\text{Total N uptake (mg pot}^{-1}\text{)} = \text{(Dry matter yield)} \times \text{(Total nitrogen concentration).}$$

$$\text{NUE (\%)} = \frac{\{\text{N uptake(mg pot}^{-1}\text{) from treated pots} - \text{N uptake (mg pot}^{-1}\text{) from control pot}\}}{\text{N applied (mg pot}^{-1}\text{)}} \times 100$$

Agronomic parameters

At harvest, the plant height was measured using a measuring tape by selecting randomly three highest plants from each pot, and their average heights were recorded. Spike length(cm) was determined at peak maturity by measuring randomly selected three spikes. The number of grains per spike was calculated by averaging the grain count of five spikes per pot. The 100-grain weight was measured using an electronic balance by weighing 100 grains from every pot. Grain yield, was determined by weighing the threshed and dried grains in each pot. The biological yield was assessed by measuring the total dry weight of the aboveground plant biomass in each pot at harvest.

Statistical Analysis

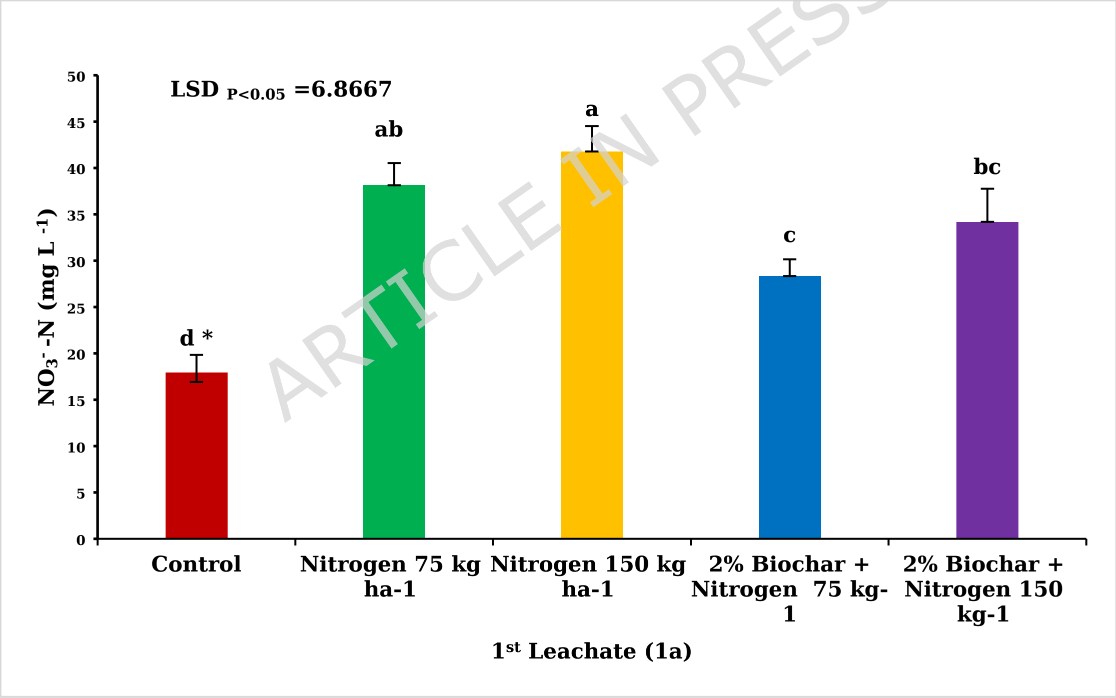
The obtained data were then statistically analyzed using ANOVA (Analysis of Variance) by using Statistix 8.1 software for the completely randomized design (CRD). The least significant difference (LSD) test was employed to compare means across all treatments ($p < 0.05$). The letters in figures show statistically significant differences between treatment means and Tables was predicated on their relative importance [22]. All figure were made using Microsoft Excel 2021.

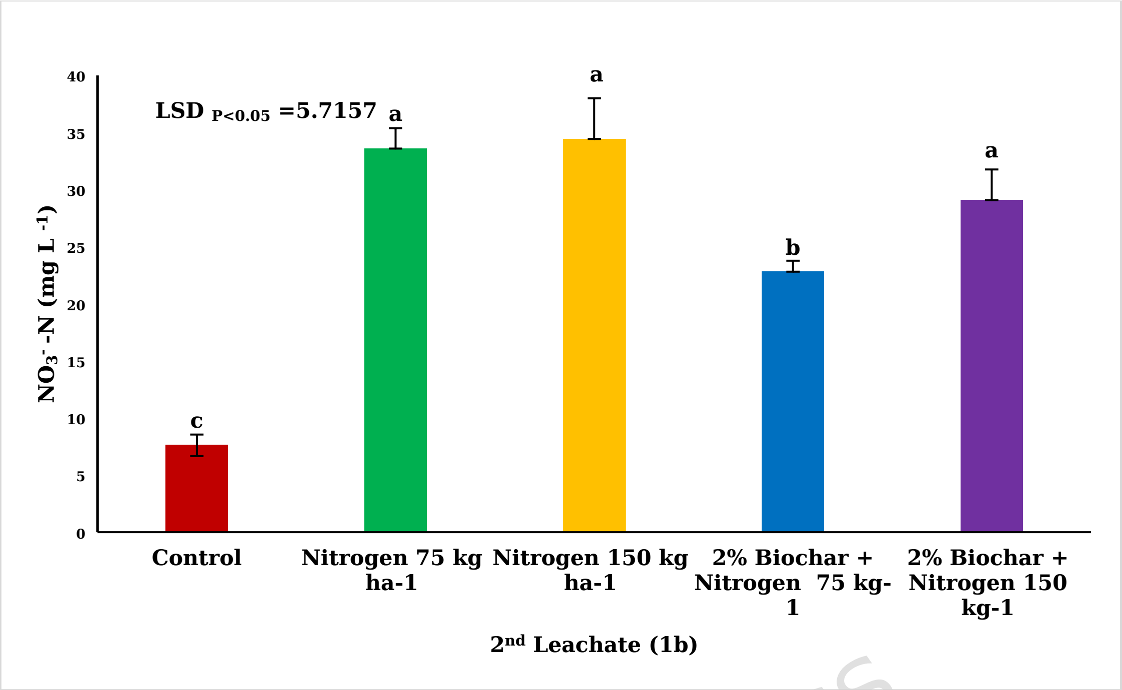
Results

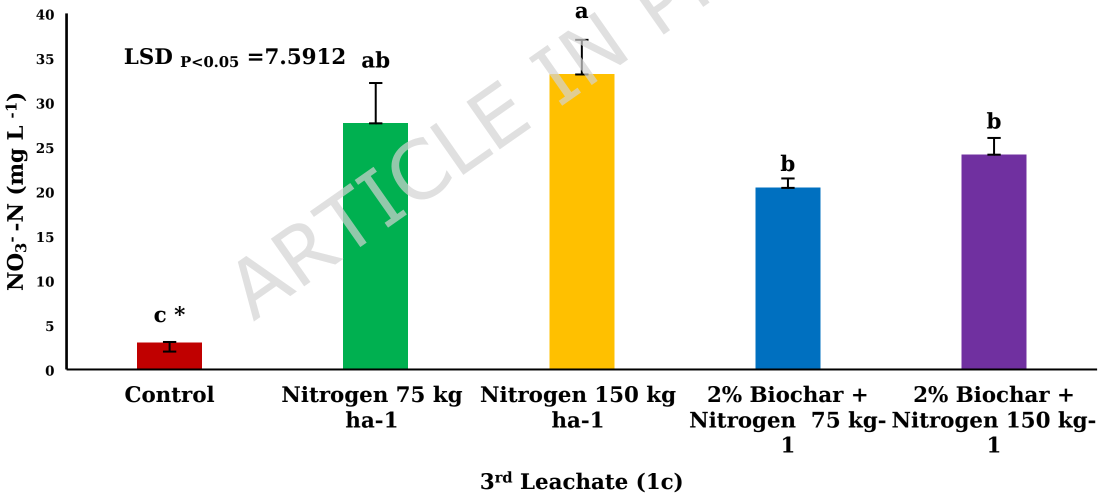
Effects of Nitrogen Rate and Biochar Amendment on Nitrate Nitrogen (NO_3^-N)

The effect of nitrogen rate and biochar amendment on the dynamics of NO_3^--N leaching at all four sampling events (14, 24, 34, and 74 DAS) were found significant ($p < 0.05$) (Figure 1a,b,c and d) . The high N rate (150 kg N ha^{-1})

in the absence of biochar resulted in the maximum levels of NO_3^--N per leaching event that were significantly higher than the moderate N applied rate (75 kg N ha^{-1}) and control. Application of biochar with 75 kg N ha^{-1} after 34 days of sowing resulted in a 29.0% reduction in NO_3^--N compared no biochar application. Similarly, the biochar applied in conjunction with 150 kg N ha^{-1} led to a 24.2% decrease in NO_3^--N (Figure 1c). This impact of mitigation measures was also apparent up to the final leaching event (after 74 days), during which 2%+75kg N ha^{-1} and 2%+150 kg N ha^{-1} exhibited the lowest NO_3^--N among all fertilized treatments (Figure 1 c and d).




LSD P<0.05 =5.7157
NO3- -N (mg L -1)
0
5
10
15
20
25
30
35
40
c
a
a
b
a
Control
Nitrogen 75 kg ha-1
Nitrogen 150 kg ha-1
2% Biochar + Nitrogen 75 kg-1
2% Biochar + Nitrogen 150 kg-1
2nd Leachate (1b)


LSD P<0.05 =7.5912
NO3- -N (mg L -1)
0
5
10
15
20
25
30
35
40
c *
ab
a
b
b
Control
Nitrogen 75 kg ha-1
Nitrogen 150 kg ha-1
2% Biochar + Nitrogen 75 kg-1
2% Biochar + Nitrogen 150 kg-1
3rd Leachate (1c)

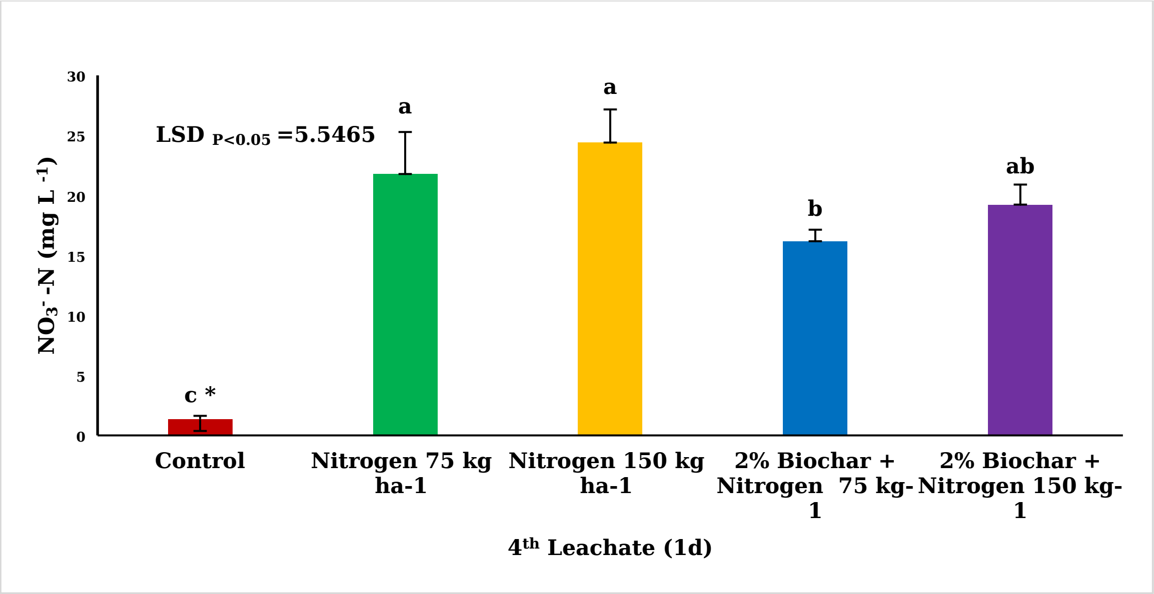


Figure 1. Nitrate-nitrogen (NO_3^--N) concentration (mg L^{-1}) in leachate as affected by biochar and nitrogen fertilizer rates at four leaching events: (1a) 14 days after sowing (DAS), (1b) 24 DAS, (1c) 34 DAS, and (1d) 74 DAS.
The error bars are standard error (SE) of mean (n=3). The letters above the error bars show significant difference with least significant difference at $P<0.05$

Soil Mineral Nitrogen and Nitrogen Use Efficiency (NUE)

Application of N and biochar amendment had significant effects on the mineral nitrogen (mg kg^{-1}) and NUE in soil ($p < 0.05$). The 2% biochar application in combination with 150 kg N ha $^{-1}$ recorded the highest MN concentration that was significantly higher than other treatments. The biochar applied with 75 kg N ha^{-1} produced soil MN levels (26.69 mg kg^{-1}) that did not differ significantly from the higher N rate applied alone (28.13 mg kg^{-1}) ($P > 0.05$). This indicates biochar efficiency to increase N retention in soil despite lower fertilizer application rates. Similarly, the highest NUE (30.70%) was observed in the 2% biochar-amended with 75 kg N ha^{-1}, followed 150 kg N ha⁻¹ (23.77%) (Supplementary Table S1). Conversely, the non-biochar treatments exhibited lower values of NUE (Table 2) .

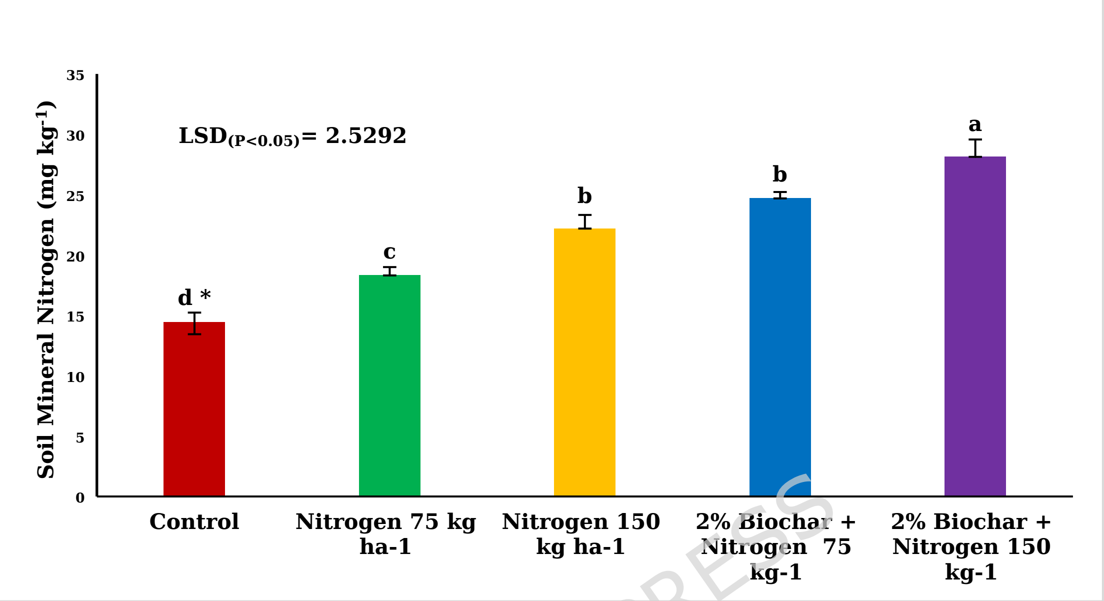


Figure 2. Post harvest mineral nitrogen (mg kg^{-1}) in soil as influenced by the application of biochar with different nitrogen rates
The error bars are standard error (SE) of mean (n=3).The letters above the error bars show significant difference with least significant difference at P<0.05

Table 2. Nitrogen use efficiency (%) as affected by biochar and nitrogen fertilizer rates

Nitrogen Applications	N use efficiency (%)
Control	-
Nitrogen 75 kg ha^{-1}	18.57 ± 10.02
Nitrogen 150 kg ha^{-1}	13.49 ± 3.91
2%Biochar+ Nitrogen 75 kg ha^{-1}	30.70 ± 3.15
2%Biochar+ Nitrogen 150 kg ha^{-1}	23.77 ± 2.55

Values denote the mean of 3 replications. Error bar indicate the standard error (SE) of the mean (n = 3).

Plant N and agronomic parameters

The application of N fertilizer and biochar had a significant impact on all growth parameters, yield, and N uptake measured in wheat (P<0.05). The highest values for grain yield (22.76 g pot $^{-1}$), biological yield (68.34 g pot^{-1}), N uptake (832.63 mg pot^{-1}), plant height (65.76 cm), spike length (9.06 cm), and 100-grain weight (3.39 g) were consistently achieved in 2% biochar with 150 kg N ha^{-1} followed 75 kg N ha^{-1} and was significant then no biochar treatments (Table 3) .

Table 3: Wheat nitrogen concentration (%), total N uptake (mg pot^{-1}), and agronomic parameters as affected by biochar and nitrogen fertilizer rates

Nitrogen applications	N Concentration (%)	N uptake (mg pot^{-1})	Plant height (cm)	Spike length (cm)	100 grain weight (g)	Biological yield (g pot^{-1})	Grain Yield (g pot^{-1})
Control	1.03 ± 0.03 b*	572.33 ± 13.45 c*	51.16 ± 0.46 c*	7.46 ± 0.09 c*	3.02 ± 0.01 d*	57.06 ± 0.84 c	18.34 ± 0.14 c*
Nitrogen 75 kg ha^{-1}	1.09 ± 0.07 ab	674.0 ± 52.68 bc	53.30 ± 0.76 c	8.10 ± 0.21b	3.06 ± 0.01 d	61.73 ± 0.79 b	19.52 ± 0.09 b
Nitrogen 150 kg ha^{-1}	1.12 ± 0.06 ab	720.03 ± 42.21 b	57.96 ± 0.84 b	8.66 ± 0.12 a	3.16 ± 0.01 c	64.06 ± 0.96 b	20.34 ± 0.12 ab
2%Biochar+ Nitrogen 75 kg ha^{-1}	1.13 ± 0.03 ab	740.40 ± 17.18 ab	58.30 ± 1.56 b	8.83 ± 0.09 a	3.27 ± 0.04 b	65.16 ± 0.88 ab	21.84 ± 0.19 ab
2%Biochar+ Nitrogen 150 kg ha^{-1}	1.22 ± 0.05 a	832.63 ± 27.91 a	65.76 ± 0.81 a	9.06 ± 0.09 a	3.39 ± 0.03 a .	68.34 ± 1.39 a	22.76 ± 0.19 a
LSD (P<0.05)	0.1665	110.13	2.7537	0.4599	0.0726	3.6438	1.0882

Values denote the mean of 3 replications meanwhile small letters indicates the significance differences among the treatments at P<0.05. Error bar indicate the standard error (SE) of the mean (n = 3).

NO$_3^-$-N losses (mg pot^{-1})

Nitrogen losses (mg pot^{-1}) are depicted in the Table 4. Biochar application with different levels of N significantly influences NO$_3^-$-N losses. N applied without biochar exhibited the maximum losses during the experiment with a measured value of 9.69mg pot^{-1} by application of 75kg N ha^{-1} and 10.70 mg pot^{-1} from 150 kg N ha^{-1}.Futhermore, 2% Biochar application with 75 kg ha $^{-1}$ lowered the cumulative loss of NO$_3^-$-N by 27.6% relative the same rate N applied alone. Similarly, biochar applied at the rate of 150 kg ha^{-1} showed a reduction of 20.3% relative to the same rate applied without biochar.

Table 4: Cumulative NO_3^--N loss (mg pot^{-1}) and % reduction with biochar amendment

Treatments	Cumulative NO_3^--N Leaching (mg pot^{-1})	% Reduction in NO_3^--N observed by the addition of biochar
Control	2.40 ± 0.11 c	—
Nitrogen 75 kg ha^{-1}	9.69 ± 0.99 b	—
Nitrogen 150 kg ha^{-1}	10.70 ± 1.05 a	—
2% Biochar + Nitrogen 75 kg^{-1}	7.02 ± 0.17 b	27.6% reduction (compared to treatment 2)
2% Biochar + Nitrogen 150 kg^{-1}	8.53 ± 0.76 ab	20.3% reduction (compared to treatment 3)

Values denote the mean of 3 replications meanwhile small letters indicates the significance differences among the treatments at $P<0.05$. Error bar indicate the standard error (SE) of the mean (n = 3).LSD ($P<0.05$)=(2.36)

Discussion

Nitrogen leaching from coarse-textured alkaline soils was reduced by applying 2% biochar along with different doses of N. In a controlled greenhouse pot experiment, nitrate (NO_3^-) leaching, N use efficiency, and wheat performance were assessed. The temperature was kept constant to prevent environmental impacts [23]. Thus, the changes in NO_3^- leaching, NUE, and crop yield can solely be examined by the use of biochar and N applications. Our findings show that biochar retains N in the soil and reduces NO_3^- leaching primarily due to increased AEC and physical entrapment of nitrates in the biochar pores. These results are consistent with the early findings of Luo et al. (2025) [24], who reported that biochar reduces NO_3^- leaching by 15–70% through mechanisms like surface adsorption, ion exchange, and pore entrapment. Application of biochar substantially enhances the physical properties of soil and nutrient retention thereby enhances the soil fertility and crop yield through nutrient availability [25] .

Optimum N in soil is an indicator of soil fertility that is enhanced with the co-application of organic sources and inorganic fertilizers such as biochar with N fertilizer[26] [27] . Mineral nitrogen (MN) in soil varied with biochar application and N rates, with 2% biochar incorporating 75 and 150 kg N ha^{-1} showing highest MN of 26.69 and 28.13 mg kg^{-1} as compared to the sole same application rates. The change observed in MN through biochar application might be due to the characteristics of the biochar for example its high CEC and surface functional groups likely retained NH_4^+ in the soil while its porous nature restricts N from rapid mineralization [28]. These results confirm that co-application of biochar with N fertilizer enhances nutrient cycling and N retention in coarse-textured alkaline soils. The enhanced N retention observed in conjunction with biochar application is of particular significance, considering the role of unretained NO_3^--N in initiating cumulative N leaching and inducing environmental risks.

Excessive N fertilizer application poses environmental hazards alongside its agronomic benefits[29] and therefore should be given special attention. The cumulative reduction (20–28%) observed in NO_3^- through biochar application might be due to performance and properties of the biochar in retaining N in the soil with coarse texture nature. Li et al.(2021)[30] reported that co application of biochar with N fertilizer can reduce cumulative N losses by enhancing N retention in soil depending on biochar properties. The study's potential implication is improving N availability and reducing environmental risks by selecting a particular biochar type that improves nutrient availability with long-term stability.

Nitrogen is the most limiting nutrient for plant production. The enhancement in NUE observed in biochar- treated pots demonstrates N retention in soil taken up by plant [31]. Coarse texture soil therefore remains poor in nutrient availability [32]. In our study, the highest NUE was observed when 2% biochar was applied with lower N rates i.e. 75 kg N ha^{-1}. This indicates that biochar is particularly effective in lower rates of N due to less N losses from applied N fertilizer [33]. Maximum plant N uptake also results in higher NUE showing that applied fertilizer is used effectively [34]. The performance of biochar applied with N fertilizer in terms of NUE was higher as biochar enhances both physical properties of the soil and root development.

Plant parameters, such as N concentration , N uptake, growth and yield were significantly affected by incorporation of biochar with N fertilizer. A notable enhancement was found in all these parameters in biochar-treated pots. These improvements were attributed to several interrelated mechanisms. (i) Biochar retains MN in soil rhizosphere that is taken up by plant at early growth stages [35], (ii) the higher N concentration in plant tissues and uptake indicates biochar not only retains N in soil but also enhances the physiological availability[36] and (iii) the properties of the biochar, for example porosity and WHC maintaining a favorable condition for root proliferation [37].

Over the past years, there has been an increasing interest in biochar as a soil amendment to reduce NO_3^- leaching and to improve the efficiency of N-utilization [38]. Biochar enhances N retention by increasing CEC, AEC, and providing porous surfaces for ion adsorption [39] [40]. As hypothesized in the present study, the application of 2% biochar significantly reduced cumulative NO_3^--N losses by 20.3–27.6% compared to N-only treatments, with the greatest reduction observed at the lower nitrogen rate of 75 kg ha^{-1}. The greater reduction at 75 kg N ha^{-1} suggests improved synchronization between soil N supply and crop demand aligning with competing hypotheses proposed by Sanford et al. (2020) [41]. In alkaline sandy loam soils, biochar can be useful as a N-limiting agent, enhancing the retention of N in forms less prone to leaching yet plant-available in the long term. Based on this, biochar application likely improved physicochemical retention, enhancing N retention and minimizing leaching losses [42]. In line with our results, Purkaystha et al. (2025)[43] found that biochar use in coarse-textured soils led to a decrease in nutrient leaching potential due to enhanced water and nutrient retention capacity. The higher retention of N in pots amended with biochar clearly led to high post-harvest soil MN and higher plant N uptake. The chemistry of biochar, along with its interactions with the soil matrix, has been demonstrated to play a pivotal role in the transformation of applied N into plant-available forms, thereby enhancing N supply and efficiency [44]. Reduced NO_3^- leaching in the mid-to-late growing phase (34-74 days after sowing) was attributed to higher N retention levels due to biochar. These results emphasize the key role of biochar in alleviating NO_3^- leaching and maximizing N cycling in alkaline coarse-textured soils, and the sustainable production of wheat.

Conclusions

The research was conducted as a short-term and single-season greenhouse pot experiment; therefore, the results should be interpreted with caution when applying them to field-scale conditions. In such controlled conditions, the application of 2% biochar + 150 kg N ha^{-1} in alkaline sandy loam soils was found to be effective in reducing NO_3^-leaching and improving soil N retention, resulting in enhanced wheat growth, yield, and N uptake. The biochar-amended treatments demonstrated clear advantages over the sole application of N, particularly in terms of reducing N loss and enhancing NUE at the optimal rates. However, it must be acknowledged that the controlled pot conditions may not fully capture the complexity of field conditions, including factors such as soil heterogeneity, climatic variability, and long-term biochar-soil interactions. Consequently, further research is required in a range of field-based investigations, encompassing various soil types and agroecological settings, in order to substantiate the longevity and scalability of these effects. Overall, the results suggest that biochar has strong potential as a sustainable soil amendment for improving N management in coarse-textured alkaline soils. However, its practical application would be best guided by field validation and site-specific considerations.

Author Contributions:

M.U. designed the experiment, collected data,. Z.K. wrote the initial draft of the manuscript analyzed the data. A.N. assisted with the experimental setup. A.K.J. provided guidance and contributed to data interpretation.

Acknowledgements:

We would like to thank Department of Soil and Environmental Sciences at The University of Peshawar, Department of Soil Science at Damascus University, and *S*oil *S*cience *S*ociety of *S*yria [*SSSS*] for their continuous support. We also appreciate the valuable assistance from all colleagues who participated in conducting the experiment and providing feedback.

Data Availability Statement:

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests Statement:

The authors declare that there are no competing interests.

Funding:

The authors declare that no funding was received for this research.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process: During the preparation of this work, the author(s) used ChatGPT (OpenAI) to support the writing process by refining grammar, enhancing clarity, and improving the structure of selected sections of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

1. Hanif MN. Factors affecting nitrogen use efficiency (NUE): meta analysis. Turk Tarim Arast Derg. 2023;10:231–42.

2. Einarsson R. Nitrogen in the food system. TABLE Explainer doi. 2024;10.

3. Govindasamy P, Muthusamy SK, Bagavathiannan M, Mowrer J, Jagannadham PTK, Maity A, et al. Nitrogen use efficiency—a key to enhance crop productivity under a changing climate. Front Plant Sci. 2023;14:1121073.

4. Butnariu M. The nitrogen cycle in the soil, impact on the environment. Environ Anal Ecol Stud. 2018;4.

5. Craswell E. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Appl Sci. 2021;3:518.

6. Essien EE, Said Abasse K, Côté A, Mohamed KS, Baig MMFA, Habib M, et al. Drinking-water nitrate and cancer risk: A systematic review and meta-analysis. Arch Environ Occup Health. 2022;77:51–67.

7. Wang Y, Liu Y, Xia L, Akiyama H, Chen X, Chen J, et al. Accounting for differences between crops and regions reduces estimates of nitrate leaching from nitrogen-fertilized soils. Commun Earth Environ. 2025;6:29.

8. Huang T, Ju X, Yang H. Nitrate leaching in a winter wheat-summer maize rotation on a calcareous soil as affected by nitrogen and straw management. Sci Rep. 2017;7:42247.

9. Khalid A, Hameed A, Tahir MF. Wheat quality: A review on chemical composition, nutritional attributes, grain anatomy, types, classification, and function of seed storage proteins in bread making quality. Front Nutr. 2023;10:1053196.

10. Manono BO, Kimiti JM, Musyoka DK. Landscape Determinants of Nitrogen Leaching Risk: Mechanisms, Impacts, and Mitigation Strategies. Nitrogen. 2026;7:20.

11. Shyam S, Ahmed S, Joshi SJ, Sarma H. Biochar as a Soil amendment: implications for soil health, carbon sequestration, and climate resilience. Discover Soil. 2025;2:18.

12. Lan T, He X, Wang Q, Deng O, Zhou W, Luo L, et al. Synergistic effects of biological nitrification inhibitor, urease inhibitor, and biochar on NH3 volatilization, N leaching, and nitrogen use efficiency in a calcareous soil–wheat system. Applied Soil Ecology. 2022;174:104412.

13. Dey S, Purakayastha TJ, Sarkar B, Rinklebe J, Kumar S, Chakraborty R, et al. Enhancing cation and anion exchange capacity of rice straw biochar by chemical modification for increased plant nutrient retention. Science of the Total Environment. 2023;886:163681.

14. Lehmann J, Joseph S. Biochar for environmental management: an introduction. In: Biochar for environmental management. Routledge; 2015. p. 1–13.

15. Jeffery S, Abalos D, Prodana M, Bastos AC, Van Groenigen JW, Hungate BA, et al. Biochar boosts tropical but not temperate crop yields. Environmental Research Letters. 2017;12:053001.

16. Kuo Y-L, Lee C-H, Jien S-H. Reduction of nutrient leaching potential in coarse-textured soil by using biochar. Water (Basel). 2020;12:2012.

17. McLean EO. Soil pH and lime requirement. Methods of soil analysis: Part 2 Chemical and microbiological properties. 1983;9:199–224.

18. Richards LA. Diagnosis and improvement of saline and alkali soils. US Government Printing Office; 1954.

19. Gee GW. Particle size analysis. Methods of soil analysis/ASA and SSSA. 1986.

20. Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. Methods of soil analysis: Part 2 chemical and microbiological properties. 1982;9:539–79.

21. Keeney DR, Nelson DW. Nitrogen—inorganic forms. Methods of soil analysis: Part 2 chemical and microbiological properties. 1983;9:643–98.

22. Bremner JM, Mulvaney C. Nitrogen—total. Methods soil analysis: part 2 chemical microbiological properties. 9: 595–624. 1983.

23. Steel RGD, Torrie JH, Dickey DA. Principles and procedures of statistics: a biometrical approach. 1997.

24. He L, Shan Y, Liu C, Cao H, Liu X, Guo Y. Prediction of bedload transport inside vegetation canopies with natural morphology. Journal of Hydrodynamics. 2024;36:556–69.

25. Luo L, Li J, Xing Z, Jing T, Wang X, Zhang G. Biochar for Mitigating Nitrate Leaching in Agricultural Soils: Mechanisms, Challenges, and Future Directions. Water (20734441). 2025;17.

26. Al-Wabel MI, Hussain Q, Usman ARA, Ahmad M, Abduljabbar A, Sallam AS, et al. Impact of biochar properties on soil conditions and agricultural sustainability: A review. Land Degrad Dev. 2018;29:2124–61.

27. Peng J, Han X, Li N, Chen K, Yang J, Zhan X, et al. Combined application of biochar with fertilizer promotes nitrogen uptake in maize by increasing nitrogen retention in soil. Biochar. 2021;3:367–79.

28. Sarfraz R, Shakoor A, Abdullah M, Arooj A, Hussain A, Xing S. Impact of integrated application of biochar and nitrogen fertilizers on maize growth and nitrogen recovery in alkaline calcareous soil. Soil Sci Plant Nutr. 2017;63:488–98.

29. Davys D, Rayns F, Charlesworth S, Lillywhite R. The effect of different biochar characteristics on soil nitrogen transformation processes: A review. Sustainability. 2023;15:16446.

30. Sainju UM, Ghimire R, Pradhan GP. Nitrogen fertilization I: Impact on crop, soil, and environment. Nitrogen fixation. 2019;9:1–9.

31. Li X, Xu S, Neupane A, Abdoulmoumine N, DeBruyn JM, Walker FR, et al. Co-application of biochar and nitrogen fertilizer reduced nitrogen losses from soil. PLoS One. 2021;16:e0248100.

32. Li C, Zhao C, Zhao X, Wang Y, Lv X, Zhu X, et al. Beneficial effects of biochar application with nitrogen fertilizer on soil nitrogen retention, absorption and utilization in maize production. Agronomy. 2022;13:113.

33. de Oliveira MW. Soil Texture: Unlocking Fertility and Productivity for Better Crops. 2025.

34. Kang S-W, Cheong YH, Yun J-J, Park J-H, Park J-H, Seo D-C, et al. Effect of biochar application on nitrogen use efficiency for sustainable and productive agriculture under different field crops. J Plant Nutr. 2021;44:2849–62.

35. Xu G, Fan X, Miller AJ. Plant nitrogen assimilation and use efficiency. Annu Rev Plant Biol. 2012;63:153–82.

36. Zhang J, Zhang L, Qiu S. Biochar amendment benefits 15N fertilizer retention and rhizosphere N enrichment in a maize-soil system. Geoderma. 2022;412:115713.

37. Kalu S, Oyekoya GN, Ambus P, Tammeorg P, Simojoki A, Pihlatie M, et al. Effects of two wood-based biochars on the fate of added fertilizer nitrogen—a 15N tracing study. Biol Fertil Soils. 2021;57:457–70.

38. Adhikari S, Mahmud MAP, Nguyen MD, Timms W. Evaluating fundamental biochar properties in relation to water holding capacity. Chemosphere. 2023;328:138620.

39. Luo L, Li J, Xing Z, Jing T, Wang X, Zhang G. Biochar for Mitigating Nitrate Leaching in Agricultural Soils: Mechanisms, Challenges, and Future Directions. Water (20734441). 2025;17.

40. Gao S, Hendratna A, Pflaum T. Assessment of biochar adsorption capacity for ammonium and nitrate and implications on soil nitrogen management. Journal of Advanced Agricultural Technologies. 2024;11:17–27.

41. Dey S, Purakayastha TJ, Sarkar B, Rinklebe J, Kumar S, Chakraborty R, et al. Enhancing cation and anion exchange capacity of rice straw biochar by chemical modification for increased plant nutrient retention. Science of the Total Environment. 2023;886:163681.

42. Sanford JR, Larson RA. Assessing nitrogen cycling in corncob biochar amended soil columns for application in agricultural treatment systems. Agronomy. 2020;10:979.

43. Zhao X, Yan X, Wang S, Xing G, Zhou Y. Effects of the addition of rice-straw-based biochar on leaching and retention of fertilizer N in highly fertilized cropland soils. Soil Sci Plant Nutr. 2013;59:771–82.

44. Purkaystha J, Prasher SO, Afzal MT, Dhiman J, Nzediegwu C. Effect of biochar, hydrogel and soil liming on nutrient leaching in a coarse-textured soil. Sustainability. 2025;17:5396.

45. Wang Z, Wang Z, Luo Y, Zhan Y, Meng Y, Zhou Z. Biochar increases 15N fertilizer retention and indigenous soil N uptake in a cotton-barley rotation system. Geoderma. 2020;357:113944.