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Biochar: an eco-friendly approach for the alleviation of nitrate leaching and augmentation of soil health

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ABSTRACT

Our study investigated the efficacy of barberry biochar in reducing nitrate leaching in arid and semi-arid area. The experiment conducted in factorial design investigating the effect of two biochar particle sizes (<1 mm and >2.8 mm) and three biochar amounts (1%, 2%, and 3% by mass ratio) on nitrate leaching in soil. Our findings revealed significant reductions in nitrate leaching upon the application of barberry biochar. The experimental treatments had a significant effect on nitrate concentration in leached water in both sampling stages. Although the initial sampling indicated non-significant variances between particle size, the clear statistical differences emerged in the second sampling. The smaller biochar particle sizes (<1 mm) recorded greater reductions by 76.3% in nitrate leaching compared to larger ones (>2.8 mm) that resulted in 66.2% reduction. Our results indicated that a 1% weight of biochar produced the lowest leaching rate, with reductions of 79.7% in the first sampling and 82.6% in the second sampling. Finer biochar particle sizes (<1 mm) were the most effective at reducing nitrate leaching, which achieved to an 80.9% reduction. Overall, barberry biochar shows potential in mitigating nitrate pollution, enhancing soil quality, and promoting agricultural sustainability. It is important to consider the optimal biochar application rate and particle size to maximize its effectiveness in reducing nitrate leaching while minimizing any potential negative impacts on crop yield. Further research is required to optimize biochar application rates, particle sizes, and long-term effects in diverse agricultural systems. Implementing biochar as a soil amendment holds promise in improving soil health, water quality, and overall sustainability.

Keywords: Agriculture performance, biochar, environmental contamination, soil fertility

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1 Introduction

Since the 1950s, there has been a notable shift towards intensive monoculture systems to meet growing food demands. These systems have heavily relied on chemical fertilizer and genetically modified cultivars, which inadvertently boosted soil and water pollution due to their heightened fertilizer requirements (Fields, 2004). While these measures were taken to ensure optimal crop yields, nearly half of the nitrogen-based fertilizers remained unabsorbed by plants, exacerbating environmental concerns (Nolan et al., 2002; Ri-Feng et al., 2014). The mobility of nitrates in the soil, due to their negative charge, results in leaching, which in turn contaminates water sources (Tylova-Munzarova et al., 2005; Goolsby, 2000). This pollution, alongside direct discharges from organic compounds, emphasizes the critical nature of water contamination. World Health Organization (WHO) established a threshold for nitrate concentration in drinking water (WHO, 2004), and with the associated health risks of excess nitrates (Brender et al., 2004; Ward et al., 2005), the need for solutions to address this issue was evident.

Besides advancements and innovations in nanotechnology for enhancing nitrogen use efficiency (NUE) (Bruun et al., 2012; Wang et al., 2022; Sahani and Sharma, 2021; Mirbakhsh, 2023) and alleviating this situation, biochar played significant role as well. Biochar identified as a promising solution in enhancing nutrient retention and improving water-holding capacity in soils (Hollister et al., 2013; Zhang et al., 2015; Siedt et al., 2021). However, any minor alteration in the quantity, size, or weight of biochar could disrupt this balance, affecting plant health adversely (Fan et al., 2014).

Given the significance of barberry cultivation in South Khorasan province and the substantial waste generated from barberry harvesting (Kafi and Balandari, 2004; Radmehr, 2010), repurposing this waste as a source for biochar production could address the region's nitrogen deficiency and associated environmental issues (Hollister et al., 2013; Zhang et al., 2015; Siedt et al., 2021). Thus, this study was initiated in 2021 to explore the potential of barberry-derived biochar in mitigating nitrate leaching from the region's loamy soils.

2 Materials and Methods

Stems resulting from harvesting and collecting barberries were obtained from the garden of the Faculty of Agriculture, Torbat University, Mashhad, Iran (35.7683° N, 51.3926° E). Stems were placed in shade conditions to dry (autumn of 2020).

2.1 Biochar production

Biochar was prepared from the discarded barberry stems in a high-temperature furnace (450 °C) through a thermochemical decomposition process under limited oxygen conditions for a duration of 6 hours. The produced biochar with a mesh size of 18 (hole size of 1 mm) was passed through. The fractions that passed through were used as treatment with particle size less than 1 millimeter. The remaining fraction with a mesh size of 7 (hole size of 2.8 mm) was sieved. The remaining portion on this mesh was used as treatment with natural particle size larger than 2.8 mm.

2.2 Soil acquisition and preparation

The soil was obtained from the surface layer (0 to 20 cm) of the nursery at Torbat University. Soil was dried in the shade and passed through a 2-mm sieve. The soil contained 13.3% clay, 42.6% silt and 44.1% sand and was thus considered silty clay according to the Khorasan province. Soil properties of the experimental site are presented in Table 1. The water requirement of the soil in its agricultural capacity was determined in the laboratory, with the process detailed.

Table 1. Physiological and chemical properties of the experimental field

Depth (cm)	0-20
Sand (%)	44.1
Silt (%)	42.6
Clay (%)	13.3
Soil EC	2.58
Saturated pH	7.3
Organic C (%)	0.511
Density (g cm^{-3})	1.38
Available N (%)	53
Available P (mg kg^{-1})	11.01
Available K (mg kg^{-1})	285.4

2.3 Soil and biochar characterization

Detailed properties of soil and the added organic matter used in the experiment are presented in Table 1 and Table 2, respectively. For this purpose, the water requirement for saturation was calculated. Initially, a container was weighed, and then 100 g of dry soil (dried in an oven for 72 h) was transferred to the container, and water was added to saturate the soil (the soil surface was shiny, and after creating a groove, it was closed by gentle tapping on the container). The container with saturated soil was weighed and then placed in an oven at a temperature of 80 °C for 48 h, after which it was weighed again. In this way, the water requirement for saturation was calculated. In a drainage container, the water requirement for saturation was added to the soil, and the container was weighed at intervals of 12 h until the weight remained constant for three consecutive measurements. Then, the water requirement for achieving field capacity was calculated (Nolan et al., 2002).

Table 3 provides a detailed overview of the biochar's physiochemical attributes, with the methodologies for these measurements previously outlined by (Li et al., 2014). An in-depth elemental analysis showcased the presence of C and N in the biochar, determined using the Flash 2000 analyzer from Thermo Fisher. Lastly, a comprehensive assessment using the Vista Axial ICP optical spectrometer by VARIAN Medical Systems, USA, revealed elements such as K, P, Ca, Mg, Fe, Mn, and Zn within the biochar.

Table 2. Some characteristics of decomposed leaf soil as a source of organic matter of the experimental field

Depth (cm)	0-20
Phosphorus (mg kg^{-1})	23.2
Mg^{+2} (mg kg^{-1})	50
Ca^{+2} (mg kg^{-1})	45.7
C: N ratio	0.358
Nitrogen (%)	0.74
Organic C (%)	5.88
Saturated pH	7.58
Soil EC	0.24

Table 3. Some characteristics of biochar produced from barberry branches at a temperature of 400 °C

Mn (mg kg^{-1})	20.99
Fe (mg kg^{-1})	33.79
Zn (mg kg^{-1})	3.11
Ca (mg kg^{-1})	1469.6
Mg (mg kg^{-1})	232.5
K (mg kg^{-1})	958.8
P (mg kg^{-1})	11.01
N (mg kg^{-1})	22.3
Organic C (%)	74.4
Saturated pH	3.7

2.4 Design and setup

The experiment was conducted using two treatment patterns of biochar particle sizes (<1 mm and >2.8 mm) and three levels of biochar amendments for each pattern. The three biochar amendment levels were 1%, 2% and 3% (mass ratios). A soil column without added biochar was used as a control. The experiment was conducted in a factorial design based on a completely randomized design with three replications at the end of 2019 and the beginning of 2020 in the Soil Science Laboratory of the Faculty of Agriculture, Torbat University.

2.5 Sampling and measurements

Pots were prepared in December 2019 and were continuously irrigated every two weeks with distilled water at 20% above the field capacity. Before the pots were filled with soil, a layer of filter paper and two gauze sealing layers were placed in the bottom of each soil column to prevent the loss of soil particles and impurities, and a thin layer of petroleum jelly was evenly smeared on the pot wall to reduce the influence of wall effects on the process of water infiltration. Each pot had a 4.7 inches height and 5.1 inches width and contained an ultrafine texture of clay, silt, and sand. The defined ratio weight of biochar was added and mixed to each pot of replicate in the block design. The temperature was 25 °C /21 °C day/night and 16 h photoperiod with an approximate humidity of 55% to get accustomed to the greenhouse situation before conducting the research with different treatments. Sampling was conducted in two stages, with a six-week interval, in April and June 2020. The nitrate content in the drained water was evaluated using a Palintest 7100 device, with the process detailed in the instruction. The percentage of particles and soil texture was determined using the hydrometer method, bulk density of soil by the cylinder method, electrical conductivity in the saturated extract of soil using an electrical conductivity meter, organic carbon by the wet oxidation method (Walkley and Black, 1934), soil nitrogen by the Kjeldahl method, phosphorus by colorimetric measurement using a spectrophotometer (Olsen, 1954).

2.6 Statistical analysis

Data was analyzed using a factorial design based on a completely randomized design, using SAS software version 9.4. Mean comparison tests based on LSD (Least Significant Difference) were executed.

3 Results and Discussion

3.1 Analysis of variance

The experimental treatments exerted a significant influence on the nitrate concentration in the leached water during both sampling stages, registering a $p<0.001$ significance (Table 4). When compared with the control in both phases, there was a marked difference ($p<0.01$). In the initial measurement, both the particle size and the biochar amount displayed significance at the 5% level. By the second measurement, this significance escalated to the 1% level. Interestingly, the interaction between particle size and biochar amount showed non-significance in the first measurement but surged to a $p<0.001$ significance in the second. The results of other investigations also demonstrated that the application of different biochar led to a reduction in leached nitrate (Downie et al., 2007; Laird et al., 2010; Li et al., 2014; Brender et al., 2004; Zhang et al., 2015). These results can be attributed to the high specific surface area and excellent anion adsorption capacity of biochar, especially under high-temperature biochar production conditions, due to the increased carbon-to-nitrogen ratio and high content of various cations in biochar composition (Table 3).

3.2 Impact of biochar on soil attributes

Several soil attributes, including its acidity, cation and anion exchange capacity, and buffering capability, undergo modifications upon biochar introduction. The magnitude of biochar's influence is governed by

Table 4. The mean squares of the treatment effects on the leached nitrate level were calculated

Source of variance (SOV)	df	Nitrate (mg L^{-1}) in 1st sampling	Nitrate (mg L^{-1}) in 2nd sampling
Treatments	6	100128.96***	126318.30***
Treatments vs. Control	2	540833.53***	685100.64***
Particle size	1	19012.50*	32004.50***
Biochar	2	16334.72*	14691.17***
Particle size × Biochar	2	4129.17 ns	5711.17***
Error	12	2663.49	254.13

Table 5. Comparison of the mean effects of particle size on the leached nitrate level

Treatments	Nitrate (mg L^{-1}) in 1st sampling	Nitrate (mg L^{-1}) in 2nd sampling
Control	643.33 a	690.33 a
<1 mm	152.22 b	137.67 c
>2.8 mm	217.22 b	216.00 b
LSD 5%	68.43	21.14

Different letters in a column indicate significant differences at P = 0.05.

Table 6. Comparison of the mean effects of biochar amount on the leached nitrate level

Treatments	Nitrate (mg L^{-1}) in 1st sampling	Nitrate (mg L^{-1}) in 2nd sampling
Control	643.33 a	690.33 a
<1 mm	152.22 b	137.67 c
>2.8 mm	217.22 b	216.00 b
LSD 5%	68.43	21.14

Different letters in a column indicate significant differences at P = 0.05.

variables such as its feedstock, production temperature, oxygen availability, and the amount applied (Lehmann and Joseph, 2015; Siedt et al., 2021). By adding biochar to clayey soil (20 g kg^{-1}), the soil's specific surface area rose from 130 to 150 m^2 (Laird et al., 2010). Furthermore, due to its high carbon-to-nitrogen ratio, biochar has a strong capacity for anion adsorption (Hollister et al., 2013; Li et al., 2014; Zhang et al., 2015), which leads to the absorption of various anions such as nitrate and consequently reduces the leaching of highly soluble anions like nitrate in water. The reduction of leaching of phosphate compounds has also been reported as a result of biochar application (Laird et al., 2010; Zhang et al., 2021). With its pronounced carbon-to-nitrogen ratio, biochar showcases robust anion adsorption capabilities, leading to reduced leaching of highly soluble anions, such as nitrate. This observation finds backing in other studies, which recorded diminished phosphate compound leaching upon biochar application (Laird et al., 2010; Zhang et al., 2021). Such reductions enhance soil fertility, thus fostering superior plant growth owing to root development optimization.

3.3 Comparative analysis

For a granular understanding, we analyzed the average nitrate content in drained water samples. Considering the non-significant interaction between particle size and biochar amount in the initial measurement (Table 4), we embarked on a comparative examination based on their average effects, as elucidated in Table 5 and Table 6. The initial sampling, influenced by particle size, is delineated in Table 5. Although particle size significantly reduced nitrate leaching relative to the biochar-absent control across both samplings, there were no statistically significant variances between particle sizes during the first sampling. The comparison of the average nitrate content in the drained water samples, considering the non-significant interaction effect of particle size and biochar amount in the first measurement (Table 5), was examined by comparing the average simple effects of particle size and biochar amount (Table 5 and Table 6).

The highest (643.33 mg L^{-1}) and lowest (152.22 mg L^{-1}) leaching rates in the first sampling were observed in the control treatment and the biochar treatment with particle size less than 1 mm, respectively. However, the differences in leaching rates due to particle size were not statistically significant in the first sampling (Table 5).

3.4 Influence of biochar quantity

The ramifications of biochar application volume on nitrate leaching are chronicled in Table 6. A consistent trend emerges, pinpointing the 1% weight of biochar as the most efficient in mitigating leaching relative to the control. As the biochar volume amplifies, its efficacy wanes—a pattern evident across both samplings. Introducing biochar might momentarily reduce nitrate's accessibility to plants; thus, moderating biochar's quantity can stave off potential yield downturns, especially during nascent growth stages (Haider et al., 2017). Notwithstanding its merits, an excessive biochar amount has been reported to adversely affect yields in crops like maize and barley. Hence, determining the precise biochar and fertilizer quantities is imperative for optimal agricultural crop performance in biochar application contexts (Haider et al., 2017). Particle sizes <1 mm and >2.8 mm led to a reduction in leaching by 76.3% and 66.2% compared to the control in the first sampling, respectively. In the second sampling, in addition to the differences between treatments and the control, there was a statistically significant difference between particle sizes, resulting in a reduction in leaching by 80.9% and 68.7%, respectively, for particle sizes <1 mm and >2.8 mm. The results of comparing the average effect of biochar application amount on nitrate leaching are presented in Table 6.

4 Conclusion

In conclusion, the experiment demonstrated that the application of biochar derived from barberry has a significant and positive impact on reducing nitrate leaching. The experimental treatments showed a clear effect in decreasing nitrate concentrations in the leached water compared to the control treatment. Both particle size and biochar amount were found to be significant factors in reducing nitrate leaching. Smaller particle sizes and higher biochar amounts resulted in greater reductions in nitrate leaching. These findings highlight the potential of biochar as an effective tool for mitigating nitrate pollution and improving soil health. Although the initial sampling indicated non-significant variances between particle size, the clear statistical differences emerged in the second sampling. Finer biochar particle sizes (<1mm) were the most effective at reducing nitrate leaching, which achieved to an 80.9% reduction. It obviously indicates that biochar application can enhance soil fertility and promote better plant growth by increasing the availability of nutrients for root uptake. It is important to consider the optimal biochar application rate and particle size to maximize its effectiveness in reducing nitrate leaching while minimizing any potential negative impacts on crop yield. Careful fertilizer management, especially during the early growth stage, is crucial to ensure an adequate nitrogen supply for crops when utilizing biochar. Overall, biochar derived from barberry holds promise as a sustainable solution for addressing nitrate pollution and improving soil quality. Further research is recommended to explore the long-term effects and refine the application strategies of biochar for specific crops and soil conditions.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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