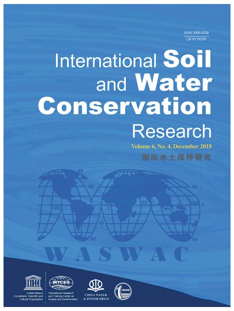

Two-Year Monitoring of Biochar Effects on Soil and Water Conservation in USLE Plots under Field Conditions

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Two-Year Monitoring of Biochar Effects on Soil and Water Conservation in USLE Plots under Field Conditions

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Biochar production

***Populus nigra* branches**

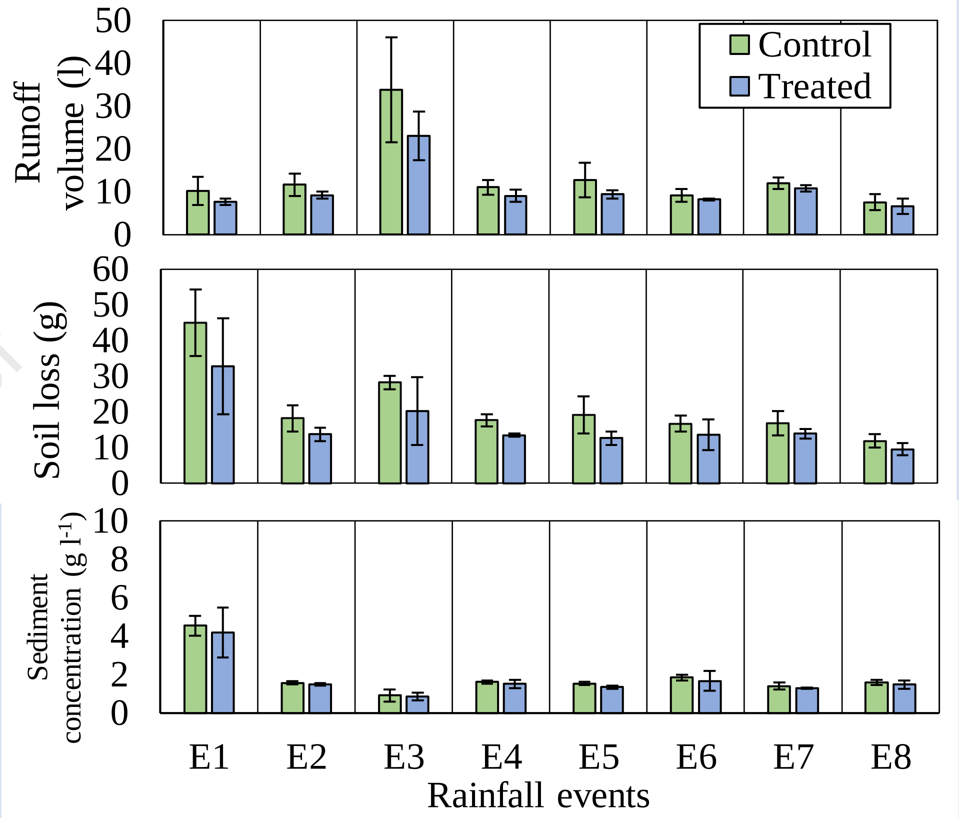
Pyrolysis

Bioch
applications
to USLE plots

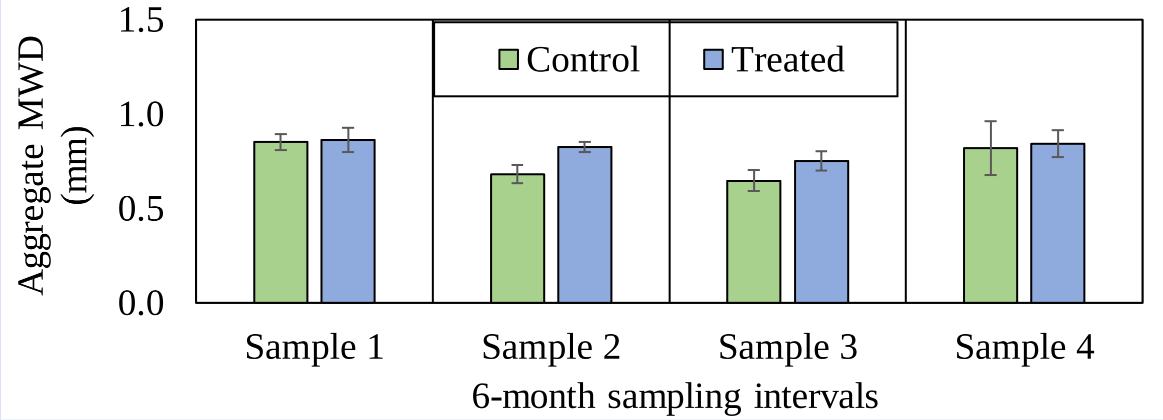
Measurement

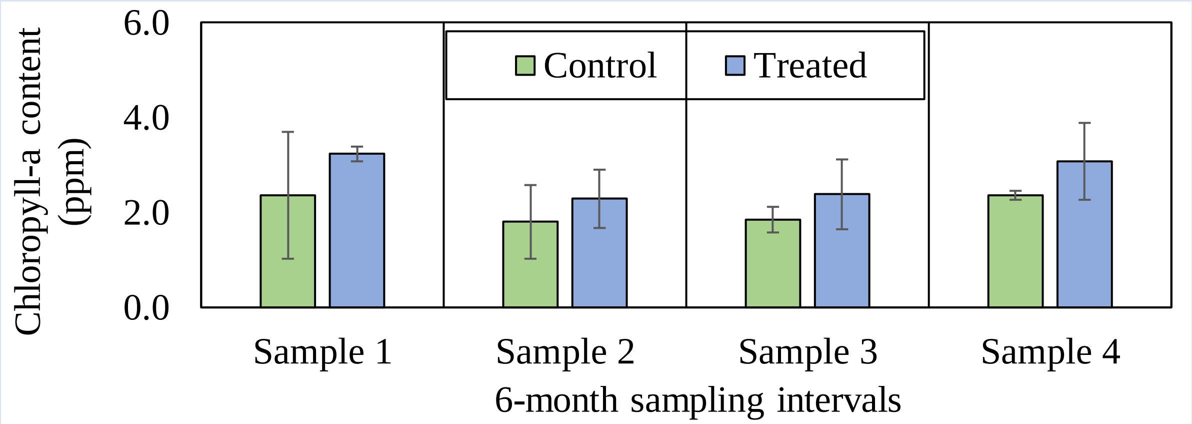
Evaluations of soil properties

Decreasing runoff volume and soil loss



Improving soil properties





Two-Year Monitoring of Biochar Effects on Soil and Water Conservation in USLE Plots under Field Conditions

Abstract

Biochar, a carbon-rich material, contributes to sustainable soil and water management by improving soil health, and understanding its behavior and both its short-term and long-term effects on soil is essential. This study investigates the impact of produced biochar from *Populus nigra* branches, applied at 32.5 t ha^{-1}, on runoff, sediment yield, and soil properties in abandoned rainfed plots. Quantitative assessments of runoff and sediment yield following natural rainfall events, coupled with biannual evaluations of soil properties, formed the basis of this investigation. The findings revealed that biochar application in treated plots led to average reductions of 20%, 24%, and 8% in runoff volume, soil loss, and sediment concentration, respectively, compared to control plots. Soil aggregate stability, evaluated through the mean weight diameter (MWD) index, together with soil porosity and soil moisture, showed significant enhancement, with all parameters attaining their maximum values one year after application. Additionally, soil chemical properties, including pH, electrical conductivity (EC), and soil organic carbon (SOC), exhibited substantial improvements, with increases of 4.5, 20.5, and 21%, respectively, relative to control samples. The independent effects of biochar and time on SOC were both significant at the 99% level. Furthermore, the biological index of chlorophyll a (Ch-a) content increased by 31%, with a statistically significant difference in response to biochar at the 95% confidence level. These findings highlight the potential of biochar derived from *Populus nigra* branches as an effective and sustainable strategy for soil and water conservation in abandoned rainfed semi-arid environments. Future research should investigate long-term biochar effects on carbon stability across soils with varying textures and organic matter.

Keywords: Abandoned Rainfed, Organic Amendments, Runoff and Sediment, Natural Rainfall, USLE Plots

1. Introduction

Soil erosion leads to the depletion of fertile topsoil (Kagabo et al., 2013) and contributes to severe environmental consequences (Assouline et al., 2017), posing significant threats to soil health and biodiversity (Qiu et al., 2021). The rate of soil loss is particularly concerning in abandoned rainfed agricultural lands, where the absence of vegetation and the persistence of non-standard tillage practices exacerbate erosion (Cerda et al., 2018; Kheirfam et al., 2020). In such areas, effective soil protection strategies must be implemented promptly to mitigate the impact of raindrop kinetic energy and splash erosion (Kheirfam et al., 2017; Gholami et al., 2019). While biological methods for controlling soil erosion are often impractical or infeasible under critical conditions, soil amendments serve as a viable alternative for soil conservation (Adekalu et al., 2007). The usage of organic amendments to improve soil structure and conditions are recognized as an efficient, cost-effective, and multifunctional approach to erosion control (Gholami et al., 2016; Chen et al., 2020). By enhancing soil stability and resilience, these amendments contribute to sustainable land management practices and long-term soil health.

Biochar, an organic soil amendment produced through the pyrolysis of diverse biological sources, has garnered increasing attention for its potential in carbon sequestration, enhancing soil fertility, and influencing soil properties (Laird et al., 2010; Gholami et al., 2019, 2022; Acharya et al., 2024). Various materials—including wood, straw mulch, bagasse, vines, molasses, manure, sewage sludge, and paper sludge—serve as feedstocks for biochar production (Gholami et al., 2022). Recent studies have examined the effects of biochar application on runoff volume and sediment yield, with most findings highlighting its efficacy in reducing runoff, minimizing soil loss, and mitigating erosion (Ding et al., 2016; Zhi-gou et al., 2017; Gholami et al., 2019; Yu et al., 2021). Additionally, biochar has demonstrated success in enhancing various soil properties, including:

- Soil structure and physical characteristics (Ibrahim et al., 2021; Sun et al., 2021; Park et al., 2023)

- Chemical properties, such as nutrient retention and pH balance (Song et al., 2015; Fan et al., 2024; Liu et al., 2024; Zhao et al., 2024)

- Organic matter content, contributing to soil fertility (Glaser et al., 2002; Kammann et al., 2011; Wang et al., 2022)

- Microbial community dynamics, fostering soil biological activity (Beheshti et al., 2018; Abbas et al., 2019; Ren et al., 2020; Chen et al., 2024b; Moyo et al., 2025)

To advancement of large-scale applications, it is essential to evaluate biochar treatments under natural field conditions and compare results with laboratory-based findings. In particular, biochar derived from *Populus nigra* branches requires further investigation to assess its long-term efficacy across diverse soil types and environmental contexts.

The study area is located within the Zarinehroud sub-watershed, a part of the larger Urmia Lake watershed in West Azerbaijan Province, Iran. This region has undergone substantial environmental changes due to the development of drainage and irrigation networks, dam construction, and population growth, which have driven land-use transitions from rangelands to rainfed and irrigated agriculture. These shifts have contributed to a decline in soil quality and productivity, leading to an expansion of abandoned rainfed agricultural lands. The resulting erosional landscapes cause both quantitative and qualitative losses of soil and water while introducing significant amounts of sediment and pollutants into Lake Urmia during rainfall events, exacerbating environmental challenges (Kheirfam et al., 2020). Given the ecological significance of Lake Urmia and the importance of studying sediment dynamics and soil degradation, this location was selected for the research project. The experiment was conducted using standard erosion plots based on the Universal Soil Loss Equation (USLE). The most widely used research plot dimensions-originally developed by Duley and Miller (1923) at

University of Missouri with dimensions of measure 1.83 × 1.22 m and designed slope with natural area slope (Alewell et al., 2019). These unit plots served as baseline conditions, enabling comparisons with various influencing factors such as topography, cropping systems, soil management practices, and conservation strategies.

This study aims to conserve soil and water resources through the application of organic amendments in field conditions. The research focuses on two primary objectives:

1- Assessing the role of biochar in reducing surface runoff and soil loss

2- Examining its impact on key physical, chemical, and biological soil properties

The experiment was conducted on an abandoned rainfed hillside in northwest Iran, using standard erosion plots under natural rainfall conditions from October 2021 to March 2024. As an uncontrolled field study, it was designed to evaluate the effects of biochar application on runoff and sediment yield, as well as its influence on soil properties, without external interventions.

2. Materials and Methods

2.1 Study area and field plots

The study was conducted in the abandoned rainfed lands upstream of the Noruzlu diversion dam, situated within the Zarinehrood sub-watershed, covering an area of approximately 12,000 m^2 within the broader Urmia Lake watershed in West Azarbaijan Province, Iran. The region experiences an average annual precipitation of 254 mm, a mean temperature of 11.4 °C, relative humidity of 62%, and annual evapotranspiration of 1,142 mm. According to the De Martonne climate classification, the area falls within a semi-arid cold climate zone (Kheirfam et al., 2020).

Six standard experimental plots were installed using galvanized sheets, following the Universal Soil Loss Equation (USLE) model. Each plot measured 1.83 × 22.1 m^2 (Duley and Miller, 1923). The most uniform hill slope in the study area was selected for their placement to ensure consistency in experimental conditions (Gholami et al., 2018). The plots were positioned on a slope with an average gradient of 25–30%, with a one-meter gap between each plot. To further minimize spatial variability, particular attention was given to selecting a geomorphologically uniform hillslope and ensuring consistent slope gradient, soil surface conditions, and land use history across all experimental plots. To facilitate data collection, tanks and pipes were installed at the end of each plot to channel and capture runoff and sediment during rainfall events (Flanagan et al., 2002). Figure 1 provides a detailed illustration of the USLE plot locations.

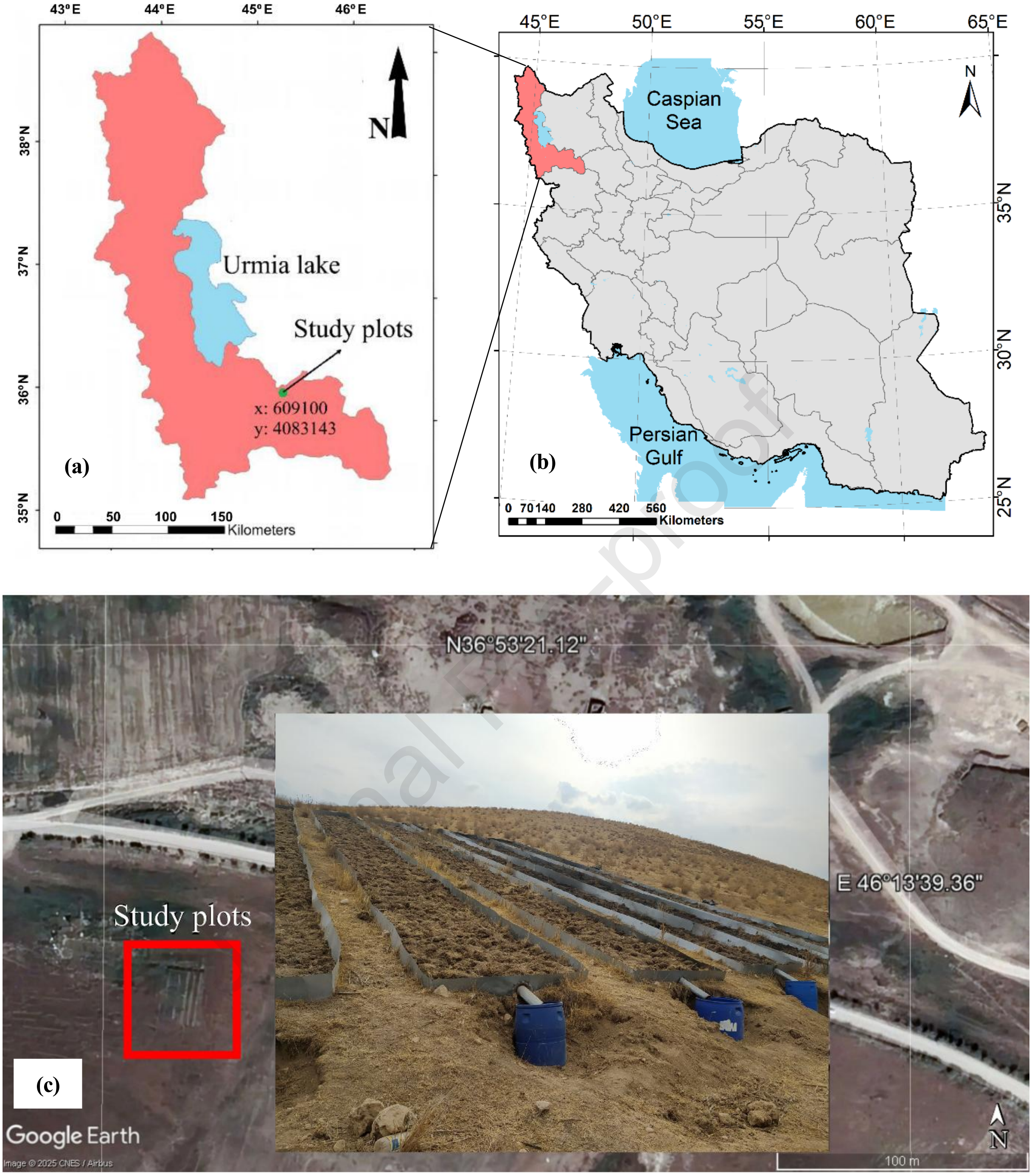


Figure 1. The location of the USLE plots in West Azarbaijan province (a) and Iran (b). Google Earth base map from Google (c), Maxar technologies, accessed April 2025.

2.2 Preparing biochar

Biochar was prepared following the identification and collection of wood waste from Tabrizi poplar (*Populus nigra*), which is abundantly available in the northwestern provinces of Iran. The pyrolysis process was carried out at a temperature of 420 °C under minimal oxygen conditions for three hours, resulting in a final product that retained 44% of its original weight (Sadeghi et al., 2016; Gholami et al., 2019). The produced biochar was then sieved through a 2 mm mesh to ensure uniform particle size (Peter, 2018). For the experiment, two treatments applied including control (without biochar application) and conservation treatments (with biochar application with the rate of 32.5 t h^{-1}), with each treatment replicated three times (Luo et al., 2017). Following preparation and transportation to the test site, the biochar was evenly distributed on the plot surfaces and incorporated into the soil to a depth of 0-5 cm. Figure 2 shows the produced biochar, its application to USLA plots, and the treated plots. Scanning electron microscope (SEM) images of the biochar at two different magnifications are presented in Figure 3. The biochar exhibits an irregular shape with a porous structure (Gholami et al., 2020). Its surface morphology is characterized by honeycomb-like pores, indicative of the carbon skeleton within its structure (Ghani et al., 2013).

Figure 2. Running the experiment including produced biochar (a), application to USLA plots (b) and the treated plots (c).

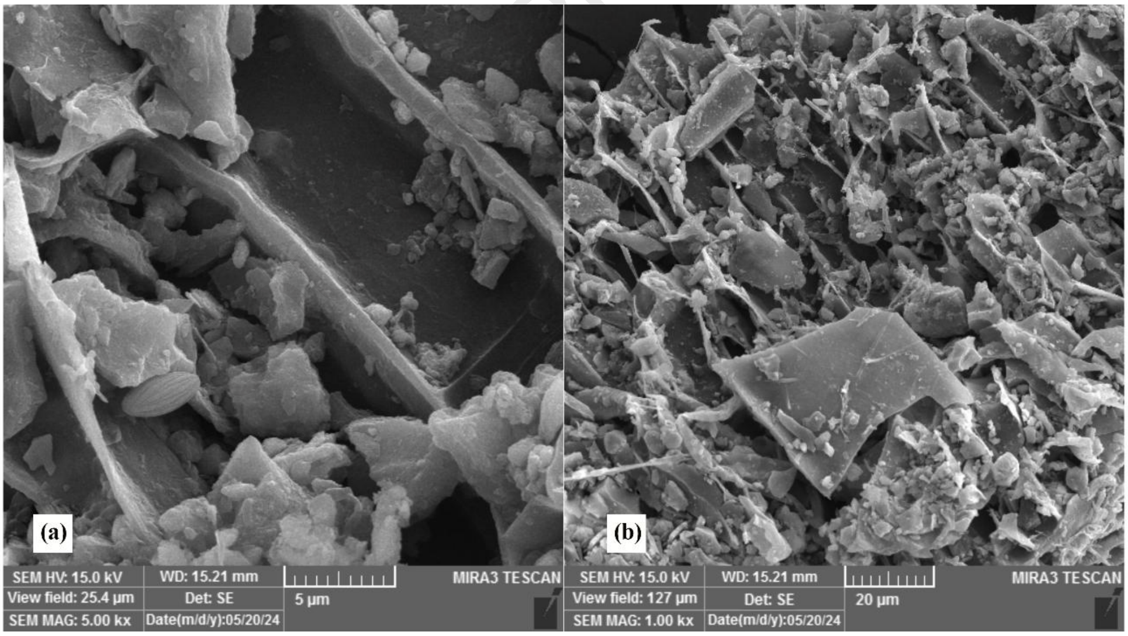


Figure 3. The SEM images of *Populus nigra* branches biochar at different magnifications, 5 μ (a) and 20 μ (b).

2.3 Rainfall events and measurement of runoff and sediment

The experiments commenced on October 23, 2021, following the application of biochar to the treated plots. Over the designated study period, eight significant rainfall events resulted in surface runoff. After each event, runoff volume was measured in collection tanks situated at the end of the plots. To analyze sediment content, the collected runoff was first homogenized by stirring, and a 1-liter sample containing both water and sediment was extracted for laboratory analysis. Sediment measurement was conducted by drying the remaining solids in an oven at 105 °C for 24 hours before weighing (Kukal and Sarkar, 2011; Sadeghi et al., 2015). To quantify and remove biochar content from the sediment in the conservation treatments, organic matter was eliminated through combustion at 450 °C for two hours (Hosking, 1938). The sediment from the control plots was treated identically; therefore, the reported soil loss values for both treatments are comparable and represent the loss of mineral soil plus any non-biochar soil organic matter. Table 1 presents meteorological data from the recorded rainfall events. The characteristics of rainfall events, viz., rainfall height (H), duration (D), average intensity (AI), and maximum 30-min (I30) intensities, rainfall kinetic energy (KE), and rainfall erosivity index (EI30), were calculated, based on Wischmeyer and Smith's (1978) method, as presented in Table 2. To understanding quantitative relationships between the runoff volume and soil loss, and the rainfalls characteristics were calculated R-squared value (R^2) and Pearson correlation (Lu et al., 2021).

Table 1
Meteorological information of recorded rainfall events in the present study

Event date	Symbol	Rainfall depth (mm)	Average temperature (°C)	Average humidity (%)	Evaporation (mm)	Snow (cm)	Event date	Symbol	Rainfall depth (mm)	Average temperature (°C)	Average humidity (%)	Evaporation (mm)	Snow (cm)
2022.01.06	E1	12.4	2.1	70.6	0	0	2022.11.27	E5	9.5	9.3	72	1.5	0
2022.01.15	E2	10.9	1.3	77.6	0	0	2023.06.13	E6	11.2	24.1	43.9	7.3	0
2022.03.04	E3	25.9	5.8	56.8	0	0	2024.02.06	E7	11.91	4.1	61.5	0	0
2022.04.30	E4	10.2	17.1	65.8	3.6	0	2024.02.20	E8	7.1	5.2	80.75	0	0

Table 2
The properties of erosive rainfall events in the study area during the experiment.

Event date	Symbol	H (mm)	D (min)	AI (mm.h-1)	I30	*KE	**EI30
2022.01.06	E1	12.4	***No data				
2022.01.15	E2	10.9	***No data				
2022.03.04	E3	25.9	1190	1.31	5.4	3.87	20.89
2022.04.30	E4	10.2	490	1.25	4.8	1.57	7.53
2022.11.27	E5	9.5	360	1.58	5.2	1.45	7.54
2023.06.13	E6	11.2	280	2.40	7.6	1.93	14.66
2024.02.06	E7	11.91	720	0.99	4	1.65	6.60
2024.02.20	E8	7.1	620	0.69	1.8	0.88	1.58

H (rainfall height), D (rainfall duration), AI (average rainfall intensity), I30 (rainfall maximum 30-min intensity), KE (rainfall kinetic energy), EI30 (rainfall erosivity index).

*KE (for rainfall intensity < 76 $mm.h^{-1}$) = $0.119 + 0.0873\log_{10} I$, and KE (for rainfall intensity > 76 $mm.h^{-1}$) = 0.283 (Wischmeyer and Smith, 1978).

**EI30 = KE × I30 (Wischmeyer and Smith, 1978).

*** No high-resolution (10-minute interval) rainfall data were recorded for this event; therefore, event-based rainfall erosivity indices could not be calculated.

2.4 Soil sampling and measurement of soil properties

A comprehensive analysis was conducted to determine soil characteristics. Particle size distribution was evaluated to classify soil texture (Xue et al., 2019), while total porosity was calculated following the method outlined by Carter and Gregorich (2007). Soil pH and electrical conductivity were measured using a HI 9811-5 multimeter. Soil organic carbon content was determined using the Walkley-Black method (Walkley and Black, 1934), total phosphorus was quantified via the Olsen method (Olsen and Sommers, 1982), total nitrogen was assessed using the Kjeldahl method (Kjeldahl, 1883), and basic microbial respiration with the method proposed by Anderson (1982). Key physical and chemical properties of the soil in the study area are summarized in Table 3. Images of the tests and sampling of soil analysis in the region are shown in Figure 4.

Table 3
Soil characteristics in USLE plots

Soil texture	Bulk density (g cm^{-3})	Total porosity (%)	pH	Electrical conductivity (µs cm^{-1})	Organic carbon (%)	Total nitrogen (%)	Total phosphorus (mg kg^{-1})	Basic microbial respiration (mg CO$_{2}$.g^{-1} day^{-1})
Loamy sand	1.04	60	9.2	176.6	0.53	0.31	17.6	0.023

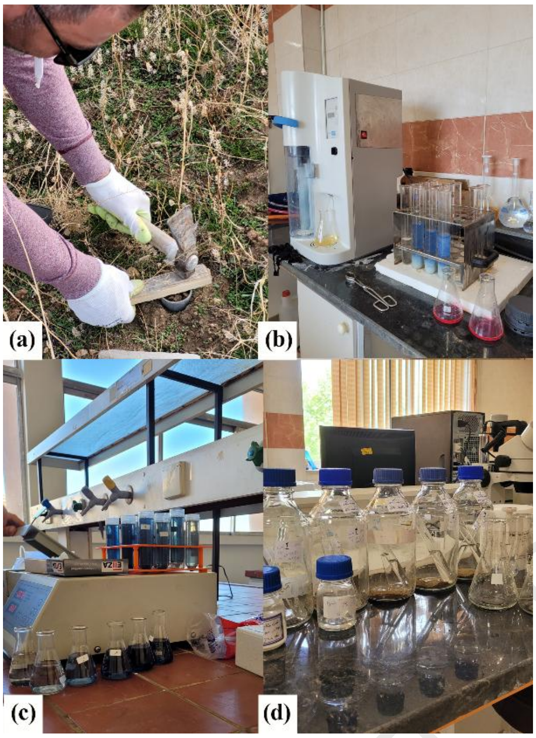


Figure 4. Soil analysis of collected soil from study area, sampling to measurement soil porosity (a), nitrogen measurement (b), phosphorus measurement (c) and measurement of basic microbial respiration (d).

Soil sampling was conducted to assess changes in soil properties resulting from biochar application. Samples were collected from the surface of both protected and control plots at six-month intervals following treatment, on April 30, 2022, November 29, 2022, May 2, 2023, and December 21, 2023. To ensure representative sampling, soil was collected from multiple points within each plot and mixed to form a composite sample. A portion of the collected soil was air-dried and passed through a four-millimeter sieve, while the remainder was refrigerated at 4 °C for biological analysis (Chamizo et al., 2012). Several key indicators were selected to evaluate changes in soil properties. Aggregate stability was assessed by determining the mean weight diameter (MWD) index using the dry sieving method (Xue et al., 2019). To determine the soil porosity (P), both the bulk density and the particle density must be measured. The bulk density is determined using the cylinder method, while the particle density of the soil is assumed to be 2.65 $g.m^{-3}$ (Carter and Gregorich, 2007). The gravimetric soil moisture content (M) was obtained from the difference between the initial and final weights of the soil samples after drying (Kheirfam and Roohi, 2020). Soil pH and electrical conductivity (EC) were measured with a Multimeter HI 9811-5. Soil organic carbon (SOC) content was quantified using the Walkley-Black method (Walkley and Black, 1934). Additionally, chlorophyll-a (Ch-a) in soil samples was measured following the method proposed by Ritchie (Ritchie, 2006) and modified by Castle (Castle et al., 2011). Images of tests to determine soil aggregate stability, pH and EC, SOC, and Ch-a content are shown in Figure 5.

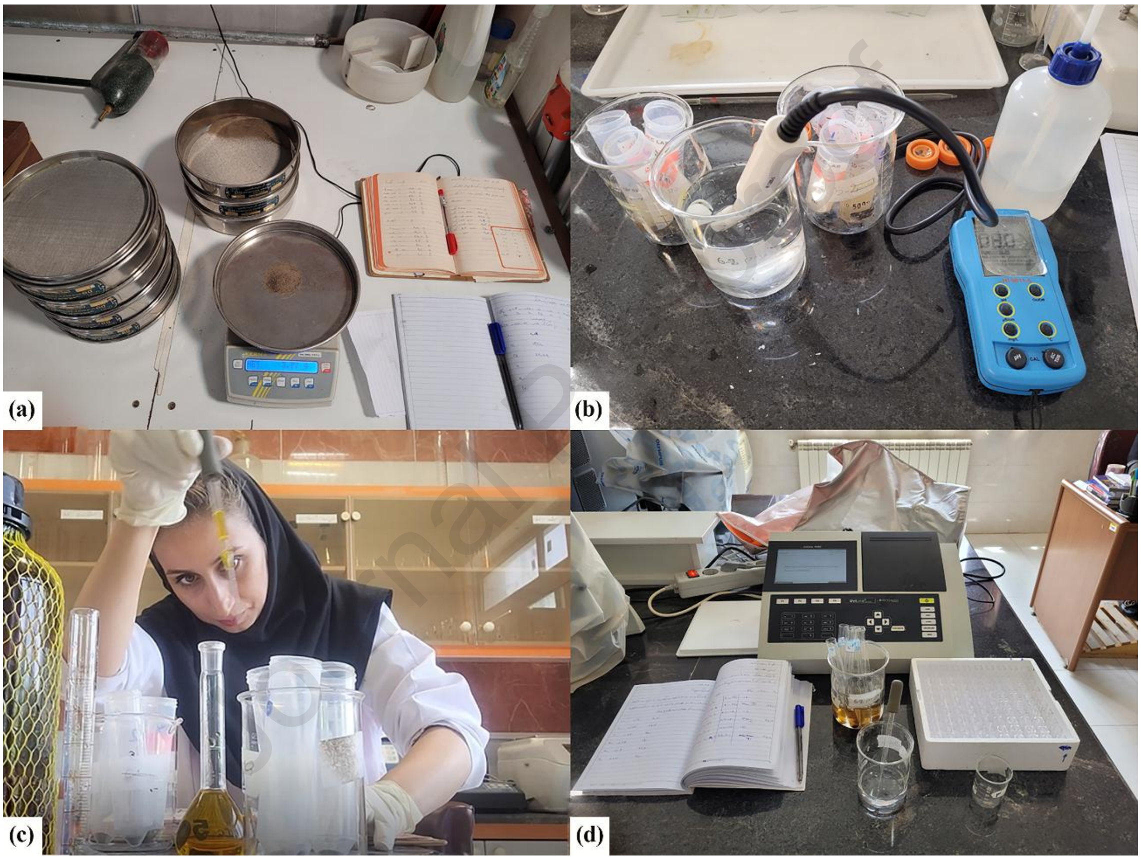


Figure 5. Investigation of soil changes before and after biochar application by measurement of aggregate mean weight diameter (MWD) (a), soil pH and electrical conductivity (EC) (b), organic carbon (OC) content (c) and chlorophyll-a content (d).

2.5 Statistical analysis

Following the completion of all experiments, a database was compiled to record runoff, sediment, and soil component data. To facilitate statistical comparisons, data normality was first assessed (Zahediasl and Ghasemi, 2012) then temporal variations in runoff and sediment behavior within each treatment were analyzed using a paired t-test (Tabachnick and Fidell, 2013). Additionally, a multivariate analysis of variance (GLM) was conducted to evaluate the effectiveness of biochar treatment and the temporal shifts in soil variables across treatments (McDonald, 2015). All statistical analyses were performed using SPSS Statistics 27.

3 Results and Discussion

3.1 Effect of biochar on surface runoff, soil loss and sediment concentration

The descriptive statistical results, including the mean and standard deviation of runoff volume, soil loss, and sediment concentration for both the biochar treatment and control, are presented in Tables 4 and 5.

Table 4

Results of the mean and standard deviation of the runoff volume in control and conservation treatments

Component	Treatment	Variable	Study events							
			E1	E2	E3	E4	E1	E6	E7	E8
Runoff Volume (l)	Control	*M*	10.17	11.63	33.77	11.03	12.67	9.1	12	7.53
		SD	3.25	2.58	12.26	1.7	4.04	1.49	1.32	1.86
	Biochar	*M*	7.67	9.2	23	9.07	9.37	8.18	10.83	6.6
		SD	0.76	0.85	5.68	1.44	0.9	0.28	0.76	1.75
Conservation Percent (%)			-24.59	-20.92	-31.89	-17.82	-26.05	-10.07	-9.72	-12.39

E1 to E8 are the dates of eight rainfall events during the experiment, including 2022.01.06, 2022.01.15, 2022.03.04, 2022.04.30, 2022.11.27, 2023.06.13, 2024.02.06, and 2024.02.20.

Table 5

Results of the mean and standard deviation of the soil loss and sediment concentration in control and conservation treatments

Component	Treatment	Variable	Study events							
			E1	E2	E3	E4	E5	E6	E7	E8
Soil loss (g)	Control	*M*	44.97	18.16	28.2	17.61	19.17	16.68	16.81	11.82
		SD	9.31	3.74	1.94	1.69	5.16	2.29	3.38	1.87
	Biochar	*M*	32.72	13.72	20.22	13.46	12.59	13.63	13.85	9.51
		SD	13.46	1.89	9.46	0.38	1.91	4.31	1.35	1.69
(%) Changes percent			-27.22	-24.44	-28.32	-23.57	-34.33	-18.33	-17.6	-19.55
Sediment concentration ($g\ l^{-1}$)	Control	*M*	4.54	1.57	0.91	1.61	1.53	1.84	1.4	1.59
		SD	0.53	0.09	0.32	0.09	0.09	0.15	0.18	0.13
	Biochar	*M*	4.18	1.49	0.85	1.51	1.34	1.66	1.28	1.47
		SD	1.31	0.07	0.21	0.22	0.08	0.51	0.04	0.21
(%) Changes percent			-7.8	-5.06	-6.77	-6.1	-12.32	-9.88	-8.53	-7.56

E1 to E8 are the dates of eight rainfall events during the experiment, including 2022.01.06, 2022.01.15, 2022.03.04, 2022.04.30, 2022.11.27, 2023.06.13, 2024.02.06, and 2024.02.20.

According to Table 4, the biochar conservation treatment led to a moderate reduction in runoff volume, averaging approximately 20% compared to the control. These findings suggest that biochar positively influences soil permeability and hydraulic properties, ultimately reducing runoff volume. This observation aligns with previous studies, such as Gholami et al. (2019), which highlighted the beneficial effects of biochar in mitigating runoff and soil loss, as well as Zhi-guo et al. (2017), who demonstrated biochar's role in runoff reduction. Additionally, Bayabil et al. (2015) reported improvements in soil hydraulic properties with the use of oak and charcoal biochar, while Sadeghi et al. (2016) found reductions in runoff within small erosion plots. Abel et al. (2013) further supported biochar's effectiveness in enhancing soil permeability and hydraulic characteristics. Table 5 reveals that biochar application resulted in an average reduction of 24% in soil loss and 8% in sediment concentration. The percentage of change observed in biochar-treated plots during specific events aligns with findings from Peng et al. (2016), Zhi-guo et al. (2017), and Gholami et al. (2019) who highlighted the significant role of biochar's high carbon content in enhancing soil particle cohesion, thereby aiding in erosion control.

Figure 6 shows the average components of runoff volume, soil loss, and sediment concentration in the control and biochar plots under erosive and effective rain events (rainfall that leads to runoff generation). The normality of the dataset was assessed using the Kolmogorov-Smirnov test (Massey, 1951), which confirmed that all measurements of runoff volume, soil loss, and sediment concentration from both control and biochar-treated plots followed a normal distribution. To compare the mean values of the studied components between treatments, a paired t-test was conducted, with results presented in Table 6. The analysis revealed that the application of biochar amendment significantly reduced runoff volume and soil loss, with a significance level of 99%. However, the comparison of mean values indicated no statistically significant difference in sediment concentration, suggesting that soil loss plays a direct role in influencing surface runoff volume.

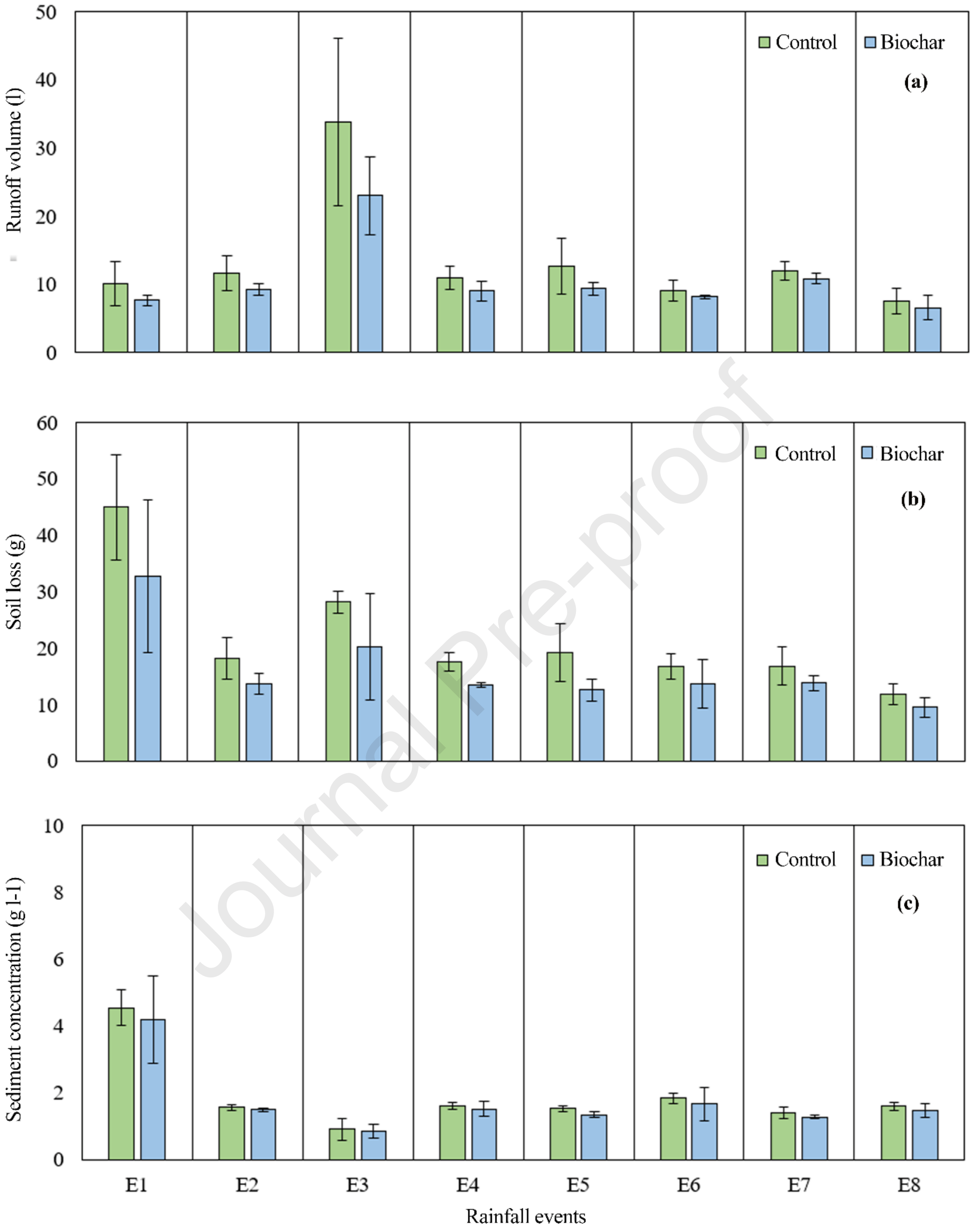


Figure 6. Means of the runoff volume (l) (a), soil loss (g) (b), sediment concentration (g l^{-1}) (c), in the control and biochar plots. E1 to E8 are the dates of eight rainfall events during experiment, including 2022.01.06, 2022.01.15, 2022.03.04, 2022.04.30, 2022.11.27, 2023.06.13, 2024.02.06, and 2024.02.20.

Table 6

Results of the Paired samples test for the runoff volume, Soil loss and sediment concentration

Paired Sample T-Test	Runoff Volume	Soil Loss	Sediment Concentration
Sig. (2-tailed)	0.009	0.001	0.174

The significant reduction in observed runoff volume clearly indicates an increased infiltration rate treated soils. This finding strongly aligns with the known mechanisms through which biochar influences soil water dynamics (Acharya et al. 2024). Specifically, the enhanced porosity resulting from biochar application creates more pathways for water entry and retention, leading to a greater capacity for infiltration and consequently, a reduction in surface runoff (Park et al., 2023).

The findings of this study align with those of Gholami et al. (2019), who reported that the presence of biochar in small erosion plots contributed to increased soil granulation, enhanced infiltration, and delayed runoff onset. However, these results contrast with Briggs et al. (2005), who suggested that soil treated with biochar exhibits greater hydrophobicity due to its higher hydrocarbon content. Smetanova et al. (2013) examined the effects of biochar derived from wood chips and tree bark on erosion control in laboratory-scale plots, concluding that biochar application reduced soil erodibility and runoff volume. Similarly, Fister et al. (2014) investigated biochar's role in soil loss mitigation using field plots and simulated rainfall, while Jien and Wang (2013) studied the biochar impacts in laboratory and field conditions and they found that the biochar had the significantly effects in reducing soil loss. Additionally, Yin et al. (2023) introduced a critical perspective on biochar's influence on soil erodibility, emphasizing that its impact on surface runoff varies based on soil conditions and rainfall intensity. Their findings indicate an initial increase in runoff at the beginning of the experiment, followed by a shift in trend after successive rainfall events.

The properties of the recorded erosive rainfall events in the study area during the experimental period are presented in Table 2. The rainfall duration (280–1190 min), rainfall height (7.1–25.9 mm), I_{30} (1.8–7.6 mm h^{-1}), KE (0.88-3.87 MJ ha^{-1} mm^{-1}), and EI_{30} (1.58-20.89 MJ mm ha^{-1}

h^{-1}) were calculated for these events. Rainfall events E1 (2022.01.06) and E2 (2022.01.15) lacked high-resolution (10-minute interval) rainfall records; therefore, event-based rainfall erosivity indices could not be determined. Based on the observed data and meteorological gauge station records, the E3 rainfall occurred on Mar 04, 2022 (D = 1190 min; I_{30} = 5.4 mm h^{-1}; EI_{30} = 20.89 MJ mm ha^{-1} h^{-1}). During this event, the measured runoff volumes were 33.77 and 23.0 L, and the soil losses were 28.20 and 20.22 g, from the control and biochar plots, respectively (Tables 4 and 5). Among all events, this rainfall (E3) exhibited the greatest rainfall height, duration, and erosivity, along with the highest runoff volume conservation percentage (31.89%). The corresponding soil loss conservation percentage (28.32%) was also substantial. The final recorded erosive rainfall, E8 (Feb 20, 2024), had a duration of 620 min; I_{30} = 1.8 mm h^{-1} and EI_{30} = 1.58 MJ mm ha^{-1} h^{-1}. This event produced runoff volume of 7.53 L and 6.6 L, and soil losses of 11.82 and 9.51 g, from the control and biochar plots, respectively (Tables 4 and 5). Although the E8 event had the lowest erosivity and consequently the smallest runoff volume and soil loss, it did not yield the lowest conservation percentages in runoff volume (12.39%) and soil loss (19.55%).

Table 7 summarizes the statistical relationships (R-squared value and Pearson correlation) between runoff volume and soil loss from the control and biochar plots, and the rainfall characteristics (H, D, AI, I_{30}, KE and EI_{30}). The Results indicated strong correlation between runoff volume (for both control and biochar plots) and rainfall characteristics, particularly H, D, and KE. Moreover, Soil loss from both plots showed strong relationships with KE and EI_{30}.

Table 7

The *R*-squared value and Pearson Correlation between runoff volume and soil loss with rainfalls characteristics.

R-squared value		H	D	AI	I30	KE	EI30
Runoff volume	Control	0.9307*	0.7235*	0.0014	0.0490	0.9052*	0.6346
	Biochar	0.9292*	0.7557*	0.0017	0.0450	0.9235*	0.6467
Soil loss	Control	0.1663	0.4483	0.0344	0.1906	0.8931*	0.7428*
	Biochar	0.1536	0.5109	0.0416	0.2239	0.9628*	0.8263*

*. Good *R*-squared value

Pearson Correlation		H	D	AI	I30	KE	EI30
Runoff volume	Control	0.965**	0.851*	-0.035	0.202	.951**	0.797
	Biochar	0.964**	0.869*	-0.039	0.212	.961**	0.804
Soil loss	Control	0.408	0.669	0.187	0.437	.945**	.862*
	Biochar	0.392	0.714	0.206	0.474	.981**	.909*

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

H (rainfall height), D (rainfall duration), AI (average rainfall intensity), I30 (rainfall maximum 30-min intensity), KE (rainfall kinetic energy), EI30 (rainfall erosivity index).

3.2 Effect of biochar on soil properties

Table 8 presents the measured values of MWD, P, M, pH, EC, SOC, and Ch-a in soil following the application of biochar amendment. The measurements were taken across two treatments (control and biochar) over four six-month intervals (Sample 1 to Sample 4). Additionally, Table 9 summarizes the results of the variance analysis conducted on these components. Figure 7 shows the comparison of average soil properties in control and treated plots at four sampling times.

Table 8

Results of aggregate mean weight diameter (MWD), soil porosity (P), soil Moisture (M), pH, electrical conductivity (EC), soil organic carbon (SOC) and chlorophyll-a (Ch-a) in control and conservation treatments

Variable	Treatment	Sample1	Sample2	Sample3	Sample4
MWD (mm)	Control	0.85	0.68	0.65	0.82
	Biochar	0.86	0.83	0.75	0.84
Changes percent (%)		1.27	21.52	16.09	2.69
P (%)	Control	No Data	60.2	63.17	64.56
	Biochar	No Data	69.9	67.29	69.1
Changes percent (%)			16.04	6.52	7.03
M (%)	Control	No Data	10.07	4.8	17.49
	Biochar	No Data	14.83	5.01	19.76
Changes percent (%)			47.34	4.53	13
pH	Control	8.93	9.17	7.73	7.23
	Biochar	9.23	9.47	8.27	7.50
Changes percent (%)		3.36	3.27	6.90	3.69
EC (μs/cm)	Control	190.0	176.7	163.3	168.3
	Biochar	216.7	206.7	213.3	203.3
Changes percent (%)		14.04	16.98	30.61	20.79
SOC (%)	Control	0.55	0.53	0.30	0.32
	Biochar	0.71	0.62	0.36	0.38
Changes percent (%)		27.71	16.35	21.35	18.75
Ch-a (μg.g^{-1})	Control	2.36	1.80	1.85	2.36
	Biochar	3.23	2.29	2.38	3.07
Changes percent (%)		37.01	27.22	28.88	30.04

Sample 1 to Sample 4 indicate soil sampling times at six-month intervals after biochar application (2022.04.30, 2022.11.29, 2023.05.02, and 2023.12.21). changes percent (%) = (Biochar – Control) / Control *100

Table 9

The analysis of variance results in different treatments for the studied variables

Dependent	Source	Type III Sum of	*df*	Mean of Square	*F*	Sig.	Partial Eta
MWD	Biochar	0.03	1	0.03	6.045	0.026	0.274
	Time	0.09	3	0.03	6.24	0.005	0.539
	Biochar × Time	0.019	3	0.006	1.287	0.313	0.194
P (%)	Biochar	168.3	1	168.3	5.52	0.037	0.315
	Time	11.35	2	5.67	0.186	0.832	0.030
	Biochar × Time	28.44	2	14.22	0.467	0.638	0.072
M (%)	Biochar	26.305	1	26.3	8.48	0.013	0.414
	Time	566.45	2	283.22	91.34	0.000	0.938
	Biochar × Time	15.55	2	7.77	2.50	0.123	0.295
pH	Biochar	0.73	1	0.73	12.69	0.003	0.442
	Time	15.17	3	5.06	87.30	0.000	0.942
	Biochar × Time	0.07	3	0.02	0.39	0.760	0.069
EC	Biochar	7526.04	1	7526.04	5.23	0.036	0.246
	Time	1078.13	3	359.38	0.25	0.860	0.045
	Biochar × Time	478.13	3	159.38	0.11	0.953	0.020
SOC	Biochar	0.05	1	0.05	11.40	0.004	0.416
	Time	0.42	3	0.14	32.59	0.000	0.859
	Biochar × Time	0.01	3	0.00	0.65	0.595	0.108
Ch-a	Biochar	2.55	1	2.55	4.97	0.040	0.237
	Time	2.79	3	0.93	1.82	0.185	0.254
	Biochar × Time	0.14	3	0.05	0.09	0.964	0.017

Mean weight diameter (MWD), soil porosity (P), soil Moisture (M), pH, Electrical conductivity (EC), Soil organic carbon (SOC), and Chlorophyll-a content (Ch-a) after biochar application (2022.04.30, 2022.11.29, 2023.05.02, and 2023.12.21).

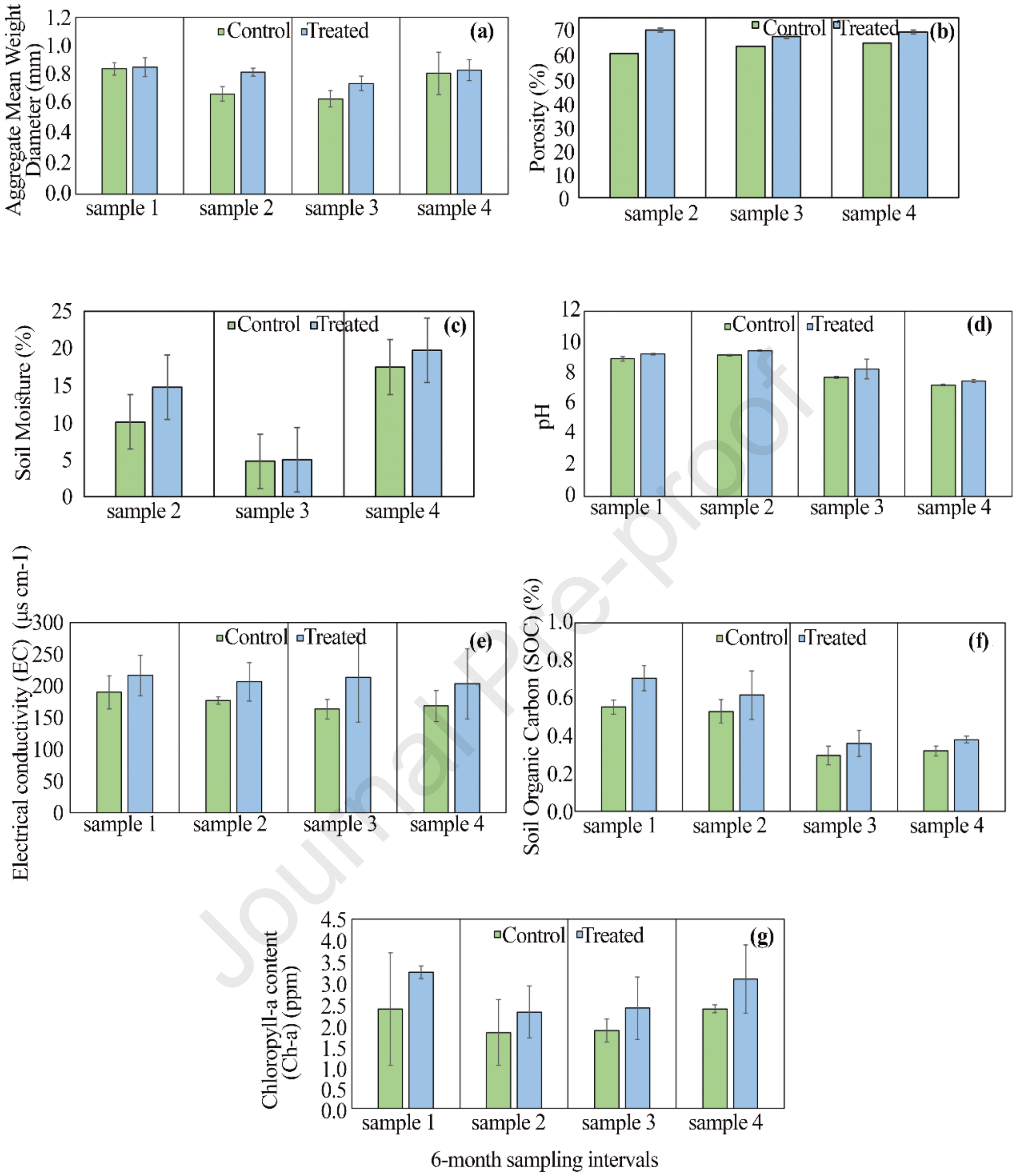


Figure 7. Comparison of the average on soil properties in control and treated plots, (a): mean weight diameter (MWD) (mm), (b): Soil porosity (P), (c): Soil moisture (M), (d): pH, (e): electrical conductivity (EC), (f): soil organic carbon (SOC), (g): chlorophyll-a content (Ch-a). Sample 1 to Sample 4 indicate the sampling time of soil at six-month intervals after biochar application (2022.04.30, 2022.11.29, 2023.05.02, and 2023.12.21).

3.2.1 Effect of biochar on aggregate stability

Aggregate stability was assessed by measuring specific pore diameter and evaluating the MWD index at four six-month intervals following biochar application in both control and treated plots (Table 8). The results indicate that the highest average MWD index (0.86 mm) was observed in the first sample from the biochar treatment, while the lowest (0.65 mm) was recorded in the third sample from the control treatment. The second and third samples exhibited incremental changes of 21.52% and 16.09%, respectively. A comparative analysis of mean MWD values across the four time intervals for both treatments is presented in Figure 7. Table 9 summarizes the variance analysis results of the MWD index in biochar and control treatments. The separate impact of biochar was statistically significant at the 95% confidence level, while the effect of time was significant at the 99% level. The effect sizes were large for both factors. Several studies have reported positive effects of biochar on soil stability. For example, Ibrahim et al. (2021) found that different levels of date palm waste biochar improved MWD and enhanced overall aggregate stability. Additionally, Sun et al. (2021) concluded in a six-year field experiment that corn biochar serves as a significant factor in increasing soil aggregate stability due to its role in enhancing MWD.

The findings suggest that biochar amendment significantly influenced aggregate stability. Six months after application, the MWD index in both conservation and control plots showed similar values. However, after the second six-month interval, the biochar treatment demonstrated a noticeable improvement, with a percentage increase of approximately 21.5% compared to the control. By the third period-1.5 years after the experiment began-measurements indicated a 16% increase in MWD under biochar treatment relative to the control. Finally, after two years, the values in both treatments returned to levels comparable to those observed in the first period. Changes in soil aggregate stability over time appear to align with seasonal weather patterns, which may be influenced by fluctuations in rainfall and temperature-key factors confirmed by Dimoyiannis (2009). The observed temporal dynamics of MWD likely reflect more complex mechanisms than seasonal climate changes. Based on the present study's findings, biochar exhibited its most pronounced effect on soil aggregate stability and structure approximately one year after application. Following soil incorporation, biochar undergoes surface oxidation and functionalization, increasing its reactivity and potential for organic–mineral interactions (Cheng et al., 2006). These aging processes may enhance associations between biochar, mineral particles, and organic matter, thereby promoting aggregate stabilization. In addition, microbial colonization and the subsequent release of microbially derived binding agents can strengthen aggregate formation through biological binding mechanisms (Liang et al., 2010; Sun et al., 2021). The delayed peak in MWD approximately one year after application may therefore correspond to the time required for biological integration. Furthermore, the initial increase in SOC may have stimulated microbial activity through a priming effect (Kuzyakov et al., 2009), whereas over longer periods, shifts in microbial turnover and carbon redistribution within aggregates may have reduced the relative treatment effect, leading to convergence between biochar and control plots. Overall, these patterns likely reflect a dynamic balance between biological stimulation and carbon stabilization processes.

3.2.2 Effect of biochar on P and M

The percentages of P and M components in three successive samplings for both control and biochar-treated plots are presented in Table 8. (Data for these two components were not available at the first sampling time.) Figure 7 illustrates the comparison of mean values of the components affected by the biochar amendment. The highest value of P, amounting to 69.9%, belongs to the first soil sample taken from the surface of the biochar-treated plots, while the lowest value, 60.2%, corresponds to the first soil sampling from the surface of the control plots.

According to the results, the mean porosity in the treated plots showed percentage changes of 16.04, 6.52, and 7.03, respectively, over time compared with the control plots. The percentage changes in component M across the three sampling times were 47.34, 4.53, and 13%, respectively. Maximum percentage changes for these two parameters were observed in the first year of the study. Based on the analysis of variance in Table 9, the effect of the biochar amendment on total porosity was statistically significant at the 95% confidence level. Moreover, the effect of biochar application was significant at the 95% level, and the effect of time elapsed was significant at the 99% level. However, the interaction effect between biochar and time on these components was not significant.

Biochar is a lightweight material with a lower density than soil minerals; its application reduces bulk density due to decreased soil mass per unit volume, thereby lowering soil compaction (Burrell et al., 2016). As reported by researchers (Lehmann and Joseph, 2009; Herath et al., 2013), the addition of biochar improves soil texture, permeability, and overall physical properties of the soil, consequently decreasing bulk density and increasing porosity. Owing to its lower density compared to mineral soil, biochar—depending on soil texture and application rate—can reduce bulk density and enhance soil porosity (Park et al., 2023; Acharya et al., 2024). Incorporation of biochar into soil also modifies pore size distribution and enhances soil water retention capacity. The increased pore volume provides favorable space for water storage within the soil (Yu et al., 2013). Furthermore, the high specific surface area of biochar contributes to improved soil water-holding capacity as a result of its addition. Accordingly, the results of the present study are consistent with the findings of several previous studies (Yu et al., 2017; Zhou et al., 2019; Acharya et al., 2024), which also confirm the significant relationship between biochar application and enhanced soil moisture retention.

3.2.3 Effect of biochar on pH and EC

The variations in average pH and EC factors, along with their percentage changes over time in control and treated plots following biochar application, are presented in Table 8. The average pH values ranged from 7.23 to 9.46, with the lowest recorded in the control plot during the final sampling and the highest observed in the treated plot during the second sampling. Similarly, the average EC varied between 163.3 and 216.6, with the lowest value found in the control plot in the third sampling and the highest detected in the treated plot in the first sampling. Notably, both components exhibited their highest percentage changes in the third interval. As indicated in Table 9, biochar application had a statistically significant effect on pH at the 99% confidence level and on EC at the 95% confidence level. Additionally, analysis of variance demonstrated that the effect of time on pH was significant at the 99% confidence level. Moreover, the effect sizes for biochar on pH and EC, as well as for time on pH, were substantial. However, time did not exert a significant effect on EC, nor did the interaction between biochar and time significantly impact pH and EC. Figure 7 illustrate the pH and EC trends across four time intervals for both control and conservation treatments. Based on sequential sampling results, changes in treated plots relative to controls were assessed as both incremental and effective for these two soil chemical parameters. On average, soil pH increased by 4.5%, while EC exhibited a 20.5% rise. The incorporation of biochar, characterized by its alkaline pH, contributed to elevated soil pH (Liang et al., 2006; Sohi et al., 2010; Kameyama et al., 2012; Zhao et al., 2024; Sharma et al., 2025). Biochar acidity is influenced by factors such as soil pH, biomass type, pyrolysis temperature, and surface charge properties (Gul et al., 2015). Liu et al. (2024) found that biochar application increased soil pH by an average of 11%, with the greatest effects occurring in acidic soils. Furthermore, the positive impact of biochar treatment on EC has been reported in this and other studies (Song et al., 2015; Zolfi-Bavariani et al., 2016; Sharma et al., 2025).

3.2.4 Effect of biochar on SOC

The impact of biochar application on the SOC component over time is presented in Table 8. Percentage changes in SOC within treated plots compared to control plots were observed as 27.71%, 16.35%, 21.35%, and 18.75% across four sampling periods. The lowest recorded average occurred in the third sampling of the control plot, while the highest was found in the first sampling of the treated plots. According to the variance analysis results in Table 8, biochar amendment and time each had a statistically significant effect on SOC at the 99% confidence level, and both factors exhibited large effect sizes. However, the interaction effect between biochar and time on SOC was not significant. A comparative analysis of SOC across four time intervals in control and conservation treatments is illustrated in Figure 7.

The findings of this study indicate that the incorporation of biochar as a carbon source had a positive and significant impact on SOC content. Lawrinenko and Laird (2015) attributed the increase in SOC following biochar application to the direct contribution of carbon within biochar. Specifically, a portion of biochar-derived organic carbon integrates into soil carbon reserves, enhancing soil organic matter levels, while another fraction undergoes oxidation, leading to the formation of negatively charged functional groups. Biochar is widely regarded as a stable form of carbon, with its primary role in soil being carbon deposition (Kameyama et al., 2012). Researchers emphasize that one of the most critical applications of biochar is carbon fixation and the subsequent enrichment of SOC (Jindo et al., 2014). Zhao et al. (2024) reported increased SOC levels following biochar application, with findings from Chen et al. (2024a) indicating that the rise ranged from 10.7% to 46.3%, depending on biochar dosage. The utilization of carbon-rich materials such as biochar is also recognized as an effective strategy for soil stabilization, organic matter preservation, and carbon sequestration (Kammann et al., 2011). By storing SOC, biochar facilitates long-term carbon accumulation (Glaser et al., 2002). Research by Wang et al. (2024) further demonstrated that biochar application led to a 33%

increase in topsoil organic carbon after a decade. In the present study, following more than two years of biochar application, SOC values in treated plots exhibited an 18.75% increase compared to control plots, reinforcing the long-term effectiveness of biochar in enhancing soil carbon content.

3.2.5 Effect of biochar on Ch-a

The variation in average Ch-a content over time in control and biochar-treated plots, along with their percentage changes, is presented in Table 8. Across all four soil sampling stages, Ch-a exhibited a consistently increasing trend, with an average increase of 31%. As shown in Table 9, the results of the variance analysis indicate that biochar amendment had a statistically significant effect on Ch-a content at the 95% confidence level, with a substantial effect size. However, the influence of time and the interaction between biochar and time were not statistically significant. A comparative analysis of Ch-a across four time intervals in control and conservation treatments is illustrated in Figure 7.

Ch-a in soil is closely linked to organic matter content and microbial activity, making it an important indicator of soil health and quality. The findings of this study suggest that increased Ch-a levels in treated plots compared to control plots reflect enhanced microbial activity in the soil. Specifically, Ch-a content is directly associated with cyanobacterial biomass within soil biocrusts (Keesstra et al., 2019). Castle et al. (2011) demonstrated that factors such as soil type, moisture levels, and extraction methods can influence Ch-a values in biological soil crusts. Additionally, Bolan et al. (2023) reported that biochar enhances the adhesion of colloidal soil particles by promoting microbial development. The study by Moyo et al. (2025) further confirmed that rising Ch-a levels indicate improved photosynthetic activity in cyanobacteria, reinforcing the notion that biochar amendments contribute to biological processes in the soil.

3.3 Practical feasibility and application considerations

The use of *Populus nigra* branches for biochar production provides a strategy to valorize abundant, low-value biomass generated by regional wood-processing industries in northwestern Iran. For this study, an application rate of 32.5 t ha^{-1} was selected to assess the potential for soil improvement and conservation under field conditions, rather than to define an economically optimized rate. Local biomass availability is sufficient to support this rate, as roughly 22% of mature poplar biomass consists of branches and pruning residues (Zhang et al., 2016), which are largely underutilized. Large-scale implementation would require coordinated collection, pyrolysis capacity, transport, and mechanized incorporation. While economic feasibility was beyond the scope of this study, literature shows that optimal application rates can differ from agronomic maxima, and future evaluations should consider indicators relevant to soil conservation, including avoided soil loss, reduced sediment transport, enhanced carbon sequestration, and ecosystem service benefits. Dose–response studies are recommended to determine the minimum effective rate and to evaluate long-term soil carbon stability across different soil types and textures.

4 Conclusion

The use of various soil amendments has garnered significant attention in water and soil conservation research. While numerous laboratory studies have validated biochar's effectiveness in improving soil properties, the present study was conducted to examine the impact of biochar derived from Tabrizi poplar trees (*Populus nigra*) on runoff, sediment, and the physical, chemical, and biological characteristics of soil under natural rainfall conditions, utilizing USLE plot-scale analysis. An evaluation of biochar’s protective effects on runoff volume, soil loss, and sediment concentration revealed statistically and practically significant reductions of approximately 20%, 24%, and 8%, respectively, compared with the control. Thes results confirm the strong potential of biochar to mitigate water erosion under natural rainfall condition. While biochar demonstrated robust short-term mitigation of soil and water losses, comprehensive techno-economic assessments are warranted to evaluate the cost effectiveness and feasibility of achieving sustained performance under high application rates for long-term, large-scale field implementation. Comparative analysis indicated a significant difference between biochar-treated soil and control soil regarding runoff volume and soil loss. Consequently, the findings suggest that biochar amendment may serve as a viable strategy for protecting abandoned dryland fields in semi-arid regions.

The study further demonstrated that biochar conservation treatment exerted a positive and significant influence on soil physical characteristics, which also varied significantly over time. Regarding chemical properties, the results indicate that biochar notably affected pH, EC, and SOC, with these components exhibiting significant differences compared to control samples. Moreover, pH and SOC underwent considerable changes over time. Ch-a, another critical parameter analyzed, displayed significant variations in response to biochar treatment and temporal progression. Based on the findings, the application of biochar produced from Tabrizi poplar tree branches at 420°C for three hours is deemed beneficial, efficient, and biologically advantageous for soil and water conservation in abandoned rainfed areas of semi-arid regions. Biochar, as a stable organic material with high water and nutrient absorption capacity, enhances soil properties by improving soil structure and aggregate stability, thereby reducing erosion and displacement. These improvements contribute to soil preservation, mitigate erosion’s detrimental effects on local ecosystems and water resources, and enhance soil fertility through increased microbial diversity.

Overall, the study underscores biochar’s potential as an effective strategy for managing water and soil resources in agricultural and natural environments. The findings not only advance knowledge of biochar’s effects on soil but also provide valuable insights for policymakers and farmers in optimizing soil and water management practices. Given the complexity of environmental processes under natural climatic conditions, further research employing extended time scales and smaller sampling intervals is necessary to yield more precise results. One of the study’s limitations was accessibility to rain gauge stations and the study site. Therefore, future studies should explore soil components in greater detail, assess long-term biochar effects on carbon stability, and investigate its impact across various soil types with differing textures and organic matter content.

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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.

Author contributions

Author A: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing - original draft. **Author B:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Author C:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Author D:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Data availability

The datasets generated during the current study are available in the Mendeley Data repository, https://data.mendeley.com/datasets/pn4xfy2j8g/1

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