Research Article

Analyzing the Effects of Organic Amendments on Soil Erosion Dynamics: A Comprehensive Study on Application Methods and Timing

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Various factors, including the type and duration of soil amendment interaction and application method, can influence soil properties and loss. This laboratory study examined the impact of different soil amendments—barberry biochar, vermicompost, poultry manure, and wheat straw residues—applied in two forms (incorporating and surface spreading) at 60-day intervals over 180 days. The investigation focused on soil texture changes, runoff volume, and sediment rate. All treatments, including the control, were replicated four times. Soil texture was assessed before and after applying amendments and rainfall, while runoff and sediment were measured using a standard rainfall simulator. Data analysis involved variance analysis and mean comparison ($P < 0.05$) through a completely randomized design using JAM13 software. The findings revealed that employing a rainfall simulator enhances the proportion of sand while diminishing the percentages of silt and clay in the soil. This study compares soil amendment methods for their impact on runoff, erosion, and sedimentation. Barberry biochar, especially when applied on the surface, consistently demonstrated superior effectiveness in reducing these issues compared to other methods. Control treatments consistently showed higher values for runoff and sedimentation. The 180-day duration proved most effective in mitigating erosion. Overall, this research emphasizes the efficacy of surface-applied barberry biochar in reducing soil erosion and sedimentation. The results carry practical implications for sustainable soil management, particularly in regions cultivating barberry, and underscore the necessity for ongoing research across diverse geographic and climatic contexts.

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1. Introduction

Soil, an indispensable component in environmental processes, stands as a paramount indicator of environmental quality (Bünemann et al., 2018). Its pivotal role in sustaining ecosystems, agriculture, and natural resource management cannot be overstated. However, the global landscape is witnessing a critical challenge – soil erosion. This phenomenon poses imminent threats to sustainable agriculture, natural resource conservation, and watershed functionality (Pimentel and Burgess, 2013; Sadeghi et al., 2015; Chalise et al., 2019). The repercussions of soil erosion extend beyond the agricultural realm, impacting the quality and quantity of soil across diverse ecosystems (Gregory et al., 2015; Vahidi et al., 2019; Vahidi et al., 2020a; Sadeghi et al., 2021; Vahidi, 2022; Vahidi et al., 2023a).

Globally, the urgency to address soil erosion becomes evident when considering its cascading effects on agriculture, environmental conservation, and the sustainable management of natural resources. To combat these challenges, an array of management measures is being explored. Among these, soil amendments emerge as a promising strategy, with organic and inorganic materials playing key roles in enhancing soil quality (Tejada and Gonzalez, 2007; Wagenbrenner et al., 2015; Sadeghi et al., 2016a; Keizer et al., 2018; Das et al., 2020; Farkas et al., 2020; Widowati et al., 2020; Sadeghi et al., 2021; Ebrahimi et al., 2022; Vahidi et al., 2022; Vahidi et al., 2023b).

Organic amendments, derived from biomass and living organisms, encompass materials such as compost, wood chips, biochar, animal manure, straw, bark, geotextiles, and sewage fertilizers (Goss et al., 2013). These materials play a crucial role in fostering soil fertility by creating optimal conditions for microbial growth and improving the microclimate environment (Kulikowska and Bernat, 2021). Simultaneously, inorganic or mineral amendments containing minerals related to soil fertility, such as gypsum for pH reduction, lime for acidic soils, and fly ash with a high trace element content, contribute to the overall soil health (Liu et al., 2017). The erosion process, intricate and interconnected, is significantly influenced by factors like soil organic carbon, aggregate stability, hydraulic conductivity, water retention ability, and overall soil fertility (Biddoccu et al., 2020; Chellappa et al., 2021).

In regions characterized by aridity and semi-aridity, where soil organic matter is often deficient due to insufficient vegetation or inadequate return of plant residues to the soil, the application of suitable and cost-effective organic amendments becomes indispensable (Shirani et al., 2002; Mohammadi et al., 2020). Plant residues and biological waste, including processed organic materials like animal manure, compost, straw, and biochar, have shown remarkable efficacy in enhancing soil properties and preventing erosion in various experiments (Gholami et al., 2014; Sadeghi et al., 2015; Wang et al., 2017; Farhoodi et al., 2019; Amoah-Antwi et al., 2020; Zareii et al., 2020; Li et al., 2021; Islam et al., 2021; Sadeghi et al., 2021; Huang et al., 2021; Yan et al., 2021; Vahidi et al., 2022).

For example, a laboratory experiment conducted in the Alborz Mountains of northern Iran demonstrated that straw mulch significantly reduced soil loss by 45.60%, outperforming manure and polyacrylamide (Sadeghi et al., 2015). Another study in China highlighted the efficacy of biochar from kitchen waste in decreasing runoff and soil erosion, underscoring the diverse effects of different amendments (Huang et al., 2021). The type of amendment, the duration of contact with soil, and the application method significantly influence their impact on soil properties and erosion resistance (Khaledi Darvishan et al., 2015; Chen et al., 2018; Siedt et al., 2021).

While research worldwide has delved into the effects of various organic amendments, biochar, and combinations on crop yield, soil fertility, erosion, and water dynamics (Doam et al., 2015), gaps in understanding persist. Despite numerous experiments, there is an essential need for comprehensive research to address uncertainties in soil amendment effects. This study aims to fill that gap by investigating the impact of various amendments, including biochar from barberry, vermicompost, poultry manure, and wheat straw, applied through complete mixing and surface spreading at 60-day intervals over 180 days, on runoff and soil loss.

The South Khorasan Province, responsible for approximately 98% of Iran's total barberry production (Vahidi, 2020b), presents a unique context for exploring the potential of processing barberry residues and producing biochar from the pruned materials of this plant. The study not only delves into temporal changes in soil erosion properties but also employs two application methods (surface mulching and complete mixing with soil). Furthermore, it compares the efficiency of these methods with other soil organic amendments, contributing a novel perspective to the existing body of research.

In summary, this research aims to:

- Evaluate soil erosion components after applying various organic amendments (barberry biochar, vermicompost, poultry manure, and wheat straw) at different time intervals (0, 60, 120, and 180 days).

- Assess the impact of different organic amendment application methods (surface application and complete mixing with soil) on soil erosion properties across various time points.
- Investigate the interaction between organic amendment types and their application methods concerning soil erosion properties.

Through these objectives, this study endeavors to advance our understanding of soil amendment effects, providing valuable insights for sustainable soil management practices.

2. Method and materials

2.1. Soil sampling site characteristics

This research was conducted at the Laboratory of the Soil Science Department, Faculty of Agriculture, University of Birjand in Iran, spanning from 2021 to 2022. The geographical coordinates of the analyzed soil samples are situated at an eastern longitude of 59° 15' 14'' and a northern latitude of 32° 51' 37''. Given that the soil characteristics of the region are influenced by land use and altitude (Vahidi et al., 2011 and 2012), this study aims to provide an explanation. The sampling site is positioned at an altitude of 1473 meters above sea level (refer to Fig. 1). The site itself lacks vegetation or specific land utility, although the surrounding area exhibits varied land uses, including agricultural lands and urban areas (refer to Fig. 1). Soil sampling was conducted during the spring season using two methods: intact and disturbed. Preliminary soil analysis revealed that the texture of the studied soils is classified as silt loam.

2.2. Soil sampling procedure

Soil samples were collected from the 0-30 cm depth, representing the average depth of crop cultivation in the region. Two distinct methods, disturbed and undisturbed (intact), were employed. Disturbed samples facilitated comprehensive mixing, while intact samples were earmarked for the surface distribution of soil amendments. Intact samples were obtained using a sharp-edged metal cube sampler with dimensions of 30 cm in length, width, and height (Fig. 2). Following the collection of disturbed samples, soils were transferred into identical containers, ensuring uniform conditions.

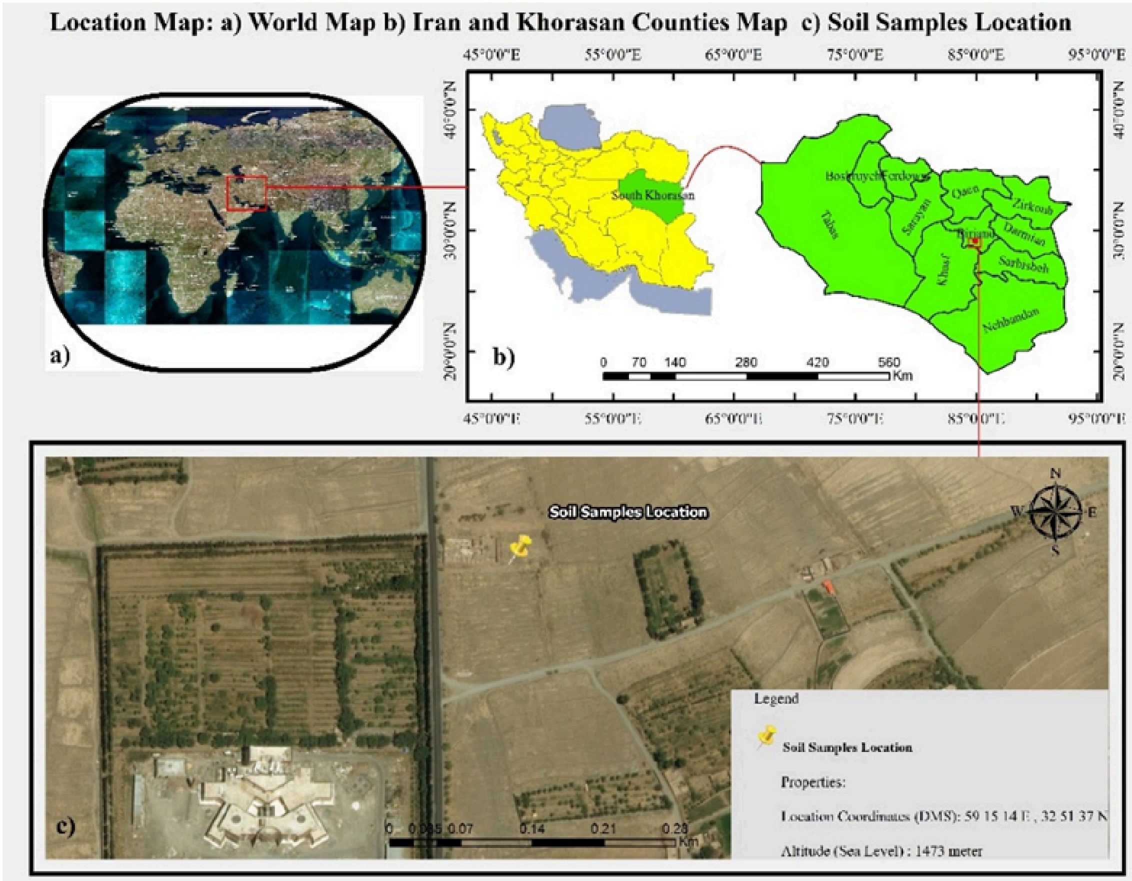

Fig. 1. The location of the investigated soil samples

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Fig. 2. The soil sampling method

2.3. Acquisition of soil amendments and determination of their characteristics

Biochar: Raw material for biochar production included pruned leaves and branches from barberry, subjected to pyrolysis at 300°C for 2 hours under limited oxygen conditions (Vahidi et al., 2022).

Vermicompost: Utilizing organic residues, vermicompost production involved a 50-day process with red earthworms (Eisenia fetida) using the bed method (Logsdon, 1994).

Poultry manure: Prepared in the Department of Animal Science at the Faculty of Agriculture, University of Birjand, poultry manure underwent a year-long production process.

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Wheat Straw: Chopped dry wheat straw harvested from the Faculty of Agriculture research farms served as the treatment.

Before application, amendments were sieved through a 2 mm mesh. A subsample underwent chemical property analysis, including carbon, hydrogen, oxygen, nitrogen, sodium, calcium, magnesium, bulk density (BD), pH, and electrical conductivity (EC). Biochar efficiency (BE) and ash biochar (AB) were determined according to Song and Guo (2012). Elemental analysis was performed using an Eager 300 EA1112 instrument, and acidity and salinity were determined as per Rajkovich et al. (2012). BD for all amendments was assessed using ASTM D-285 method (Song and Guo 2012).

2.4. Characteristics of the rainfall simulator

The rainfall simulator, a non-pressurized, portable Plexiglas model (30 x 30 cm, height 65 cm), featured a triangular appendage for runoff and sediment collection during erosion simulation (Fig. 3).

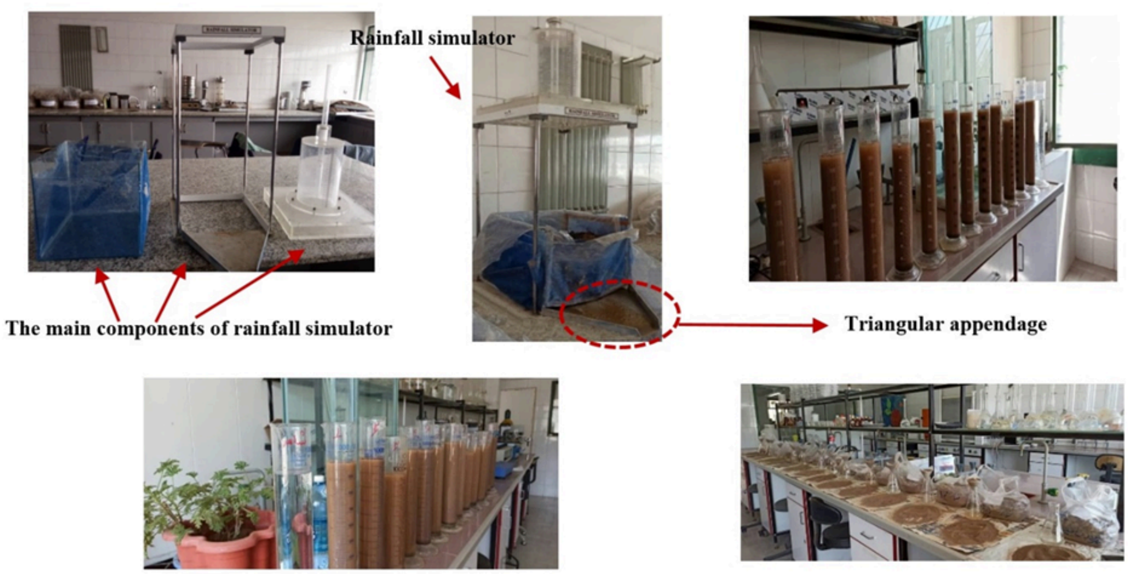

Fig. 3. Rainfall simulator and procedures for conducting research tests

2.5. Preparation of treatments and assessment of soil and erosion characteristics

All amendments were applied at a 5% level (50 grams per kilogram of soil) through two methods: complete mixing and surface spreading. Amendments included barberry biochar, vermicompost, poultry manure, wheat straw, and a control treatment. The experiment spanned 180 days with soil moisture maintained close to field capacity. Parameters measured included sand, silt, clay

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percentages, sediment discharge rate (Qs), dry weight sediment (DWS), discharge rate (Q), runoff duration, time until runoff initiation, and runoff coefficient. Soil properties were analyzed bi-monthly over 6 months.

2.6. Experimental Design and Statistical Analysis

A factorial experiment, utilizing a completely randomized design with four replications, featured five soil amendment levels, two application methods, and four measurement intervals. Analysis of variance and mean comparisons (LSD test, $P < 0.05$) were conducted using JMP 13 software. A step-by-step flowchart of the overall methodology is presented in Fig. 4.

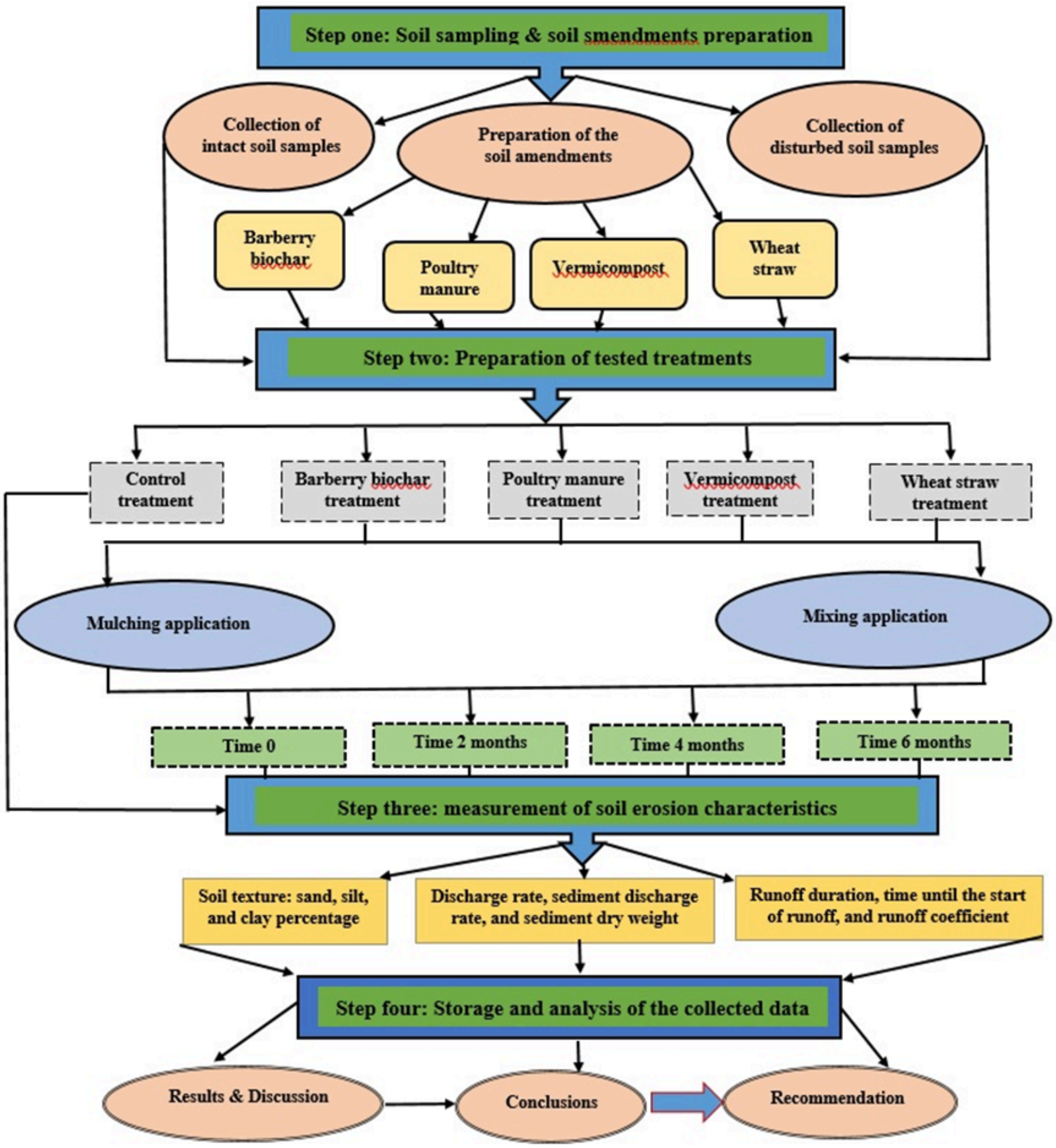

Fig. 4. Illustrates the flowchart depicting different stages of the research process

3. Results

3.1. Soil and amendment characteristics

Table 1 presents various characteristics, including biochar efficiency (BE), ash biochar (AB), elemental analysis of soil amendments, and soil properties.

3.2. Changes in sand, silt, and clay

Variance analysis results for the interaction effects of rainfall, soil amendment type, and application methods on sand, silt, and clay are summarized in Table 2.

3.2.1. Sand percentage

Following the application of the rainfall simulator, sand percentage increased consistently across all treatments. The control treatment exhibited the highest sand percentage after the simulator application, while the lowest was observed before its application. Treatments with amendments consistently showed lower sand percentages compared to the control.

3.2.2. Silt percentage

The application of the rainfall simulator led to a reduction in silt percentage across all treatments. The highest and lowest silt percentages were observed in the control treatment before and after the simulator application, respectively. Treatments with amendments displayed higher silt percentages compared to the control after the simulator application.

3.2.3. Clay percentage

The percentage of clay decreased in all treatments after rainfall simulation. The highest and lowest clay percentages were observed in the wheat straw treatment before the rainfall simulator's application and after the simulator application of a mixture of wheat straw. The clay percentages in treatments with amendments were consistently higher than those in the control after the simulator application.

Detailed results for sand, silt, and clay alterations are presented in Tables 3 and 4. Figure 5 visually depicts the trends in sand percentage across different soil amendment treatments after rainfall simulation. Figure 6 compares the percentage of sand and clay between surface application methods and a mixture of soil amendments. Figure 7 illustrates the temporal changes in sand and clay percentages at various time points following the rainfall simulator application.

The highest and lowest percentages of clay were obtained from the wheat straw treatment before the rainfall simulator's application and from the use of a mixture of straw and wheat stubble after the application of the rainfall simulator. After applying the rainfall simulator, the amounts of clay in the treatments with amendments were higher compared to the control. The results presented in Table 3 demonstrate that the use of the rainfall simulator led to an increase in the percentage of sand across all amendments and times compared to the pre-simulation period. The control treatment exhibited the highest percentage of sand after the rainfall simulator application, while the lowest percentage was observed before its application. Following the rainfall simulator application, the treatments with amendments showed lower amounts of sand compared to the control. The application of the rainfall simulator also resulted in a reduction in the percentage of clay across all treatments compared to the pre-simulation period. The treatment with wheat straw before applying the rainfall simulator had the highest clay percentage, while the control treatments, poultry manure (at 0, 60, and 180 days), and wheat straw (at times 120 and 180 days), displayed the lowest clay percentages after the rainfall simulator application at 180 days. The findings presented in Table 4 indicate that the implementation of the rainfall simulator resulted in a reduction in the percentage of silt across all treatments when compared to the pre-application period of the rainfall simulator. The treatments before the application of the rainfall simulator and the mixed method exhibited the highest and lowest silt percentages, respectively, at 120 days following the application of the rainfall simulator. The data depicted in Figure 5 illustrates an increase in the percentage of sand across all soil amendment treatments following the application of the rainfall simulator. The control and barberry biochar treatments recorded the highest and lowest percentages of sand, respectively, after the rainfall simulator was applied. Furthermore, the percentage of silt and clay decreased in all soil amendment treatments after the rainfall simulator application. The highest percentages of silt and clay were observed in the barberry biochar treatment, while the control biochar treatment exhibited the lowest percentages of silt and clay after the application of the rainfall simulator. As depicted in Figure 6, the percentage of sand increased in both surface application methods and the mixture of soil amendments following the application of the rainfall simulator. Notably, the mixed method exhibited a higher percentage of sand compared to the surface method. Conversely, the percentage of clay decreased in both the surface application method and the mixture of soil amendments after the rainfall simulator application. However, the clay percentage was higher in the surface method as opposed to the mixture. As depicted in Figure 7, the percentage of sand consistently increased across all time points following the application of the rainfall simulator. The peak values for sand percentage were observed at 0, 60, and 180 days after the rainfall simulator application. Conversely, the percentage of clay showed a consistent decrease across all investigated time points after the application of the rainfall simulator. The highest values for clay percentage were noted at 0 and 120 days after the application of the rainfall simulator.

Characteristics	Soil	Barberry biochar	Poultry manure	Vermicompost	Wheat straw
BE (%)	-	31	-	-	-
AB (%)	-	14.5	-	-	-
Oxygen (%)	-	11.8	34.1	33.9	28.4
pH	8	8.8	7.9	6.9	6.8
EC (dS/m)	0.63	4.3	3.1	1.58	3.4
C (%)	-	78.57	31.2	11.88	43.3
OC (%)	0.19	-	-	-	-
Hydrogen (%)	-	2.2	4.7	4.22	5.3
Nitrogen (%)	0.002	0.85	4.3	1.02	0.9
Phosphorous (%)	0.001	0.58	1.5	0.30	0.04
Potassium (%)	0.001	0.67	2.4	0.24	1.17
Calcium (%)	0.003	5.24	2.3	0.17	0.42
Magnesium (%)	0.001	0.15	0.02	0.06	0.10
C/N	95	84.2	7.25	11.64	48.1
Texture	Silt loam	-	-	-	-
Sand (%)	20	-	-	-	-
Silt (%)	65	-	-	-	-
Clay (%)	15	-	-	-	-
BD (gr/cm^3)	1.4	0.65	0.45	0.54	0.18
MWD (mm)	0.4	-	-	-	-
Ɵs (%)	47	-	-	-	-

Table 1. Some characteristics of soil and studied amendments

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BE: biochar efficiency, AB: ash biochar, pH: soil reaction, EC: electrical conductivity, C: carbon, OC: organic carbon, C/N: carbon to nitrogen ratio, BD: bulk density, MWD: mean weight diameter of aggregates, ϴs: saturation moisture

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Rainfall	Amendment type	Application method	Sand (%)	Silt (%)	Clay (%)
Before	**Control**	Surface	20.00 i	65.00 a	15.00 bc
		Mixture	20.00 i	65.00 a	15.00 bc
	Barberry biochar	Surface	22.00 h	62.00 b	16.00 b
		Mixture	22.00 h	62.00 b	16.00 b
	Poultry manure	Surface	23.00 h	63.00 b	14.00 cd
		Mixture	23.00 h	63.00 b	14.00 cd
	Vermicompost	Surface	22.00 h	62.00 b	16.00 b
		Mixture	22.00 h	62.00 b	16.00 b
	Wheat straw	Surface	22.00 h	59.00 c	19.00 a
		Mixture	22.00 h	59.00 c	19.00 a
After	**Control**	Surface	40.00 a	50.00 g	10.00 fg
		Mixture	40.00 a	50.00 g	10.00 fg
	Barberry biochar	Surface	27.00 g	57.50 de	15.50 b
		Mixture	26.50 g	58.00 cd	15.50 b
	Poultry manure	Surface	30.00 ef	59.00 c	11.00 f
		Mixture	33.50 c	55.50 f	11.00 f
	Vermicompost	Surface	29.00 f	57.00 de	14.00 cd
		Mixture	31.00 de	56.25 ef	12.75 e
	Wheat straw	Surface	31.50 d	55.00 f	13.50 de
		Mixture	35.50 b	55.00 f	9.50 g

Table 2. The interaction effects of rainfall, soil amendment type, and its application methods on sand, silt and clay

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Means in the columns followed by the same letter are not significantly different according to LSD test at P < 0.05.

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Rainfall	Modifier	Time (day)	Sand (%)	Silt (%)	Clay (%)
Before	Control	0	20.00 k	65.00 a	15.00 b-d
		60	20.00 k	65.00 a	15.00 b-d
		120	20.00 k	65.00 a	15.00 b-d
		180	20.00 k	65.00 a	15.00 b-d
	Barberry biochar	0	22.00 j	62.00 a	16.00 bc
		60	22.00 j	62.00 a	16.00 bc
		120	22.00 j	62.00 a	16.00 bc
		180	22.00 j	62.00 a	16.00 bc
	Poultry manure	0	23.00 j	63.00 a	14.00 de
		60	23.00 j	63.00 a	14.00 de
		120	23.00 j	63.00 a	14.00 de
		180	23.00 j	63.00 a	14.00 de
	Vermicompost	0	22.00 j	62.00 a	16.00 bc
		60	22.00 j	62.00 a	16.00 bc
		120	22.00 j	62.00 a	16.00 bc
		180	22.00 j	62.00 a	16.00 bc
	Wheat straw	0	22.00 j	59.00 a	19.00 a
		60	22.00 j	59.00 a	19.00 a
		120	22.00 j	59.00 a	19.00 a
		180	22.00 j	59.00 a	19.00 a
After	Control	0	40.00 a	50.00 a	10.00 g
		60	40.00 a	50.00 a	10.00 g
		120	40.00 a	50.00 a	10.00 g
		180	40.00 a	50.00 a	10.00 g
	Barberry biochar	0	26.00 i	57.50 a	16.50 b

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Rainfall	Modifier	Time (day)	Sand (%)	Silt (%)	Clay (%)
		60	27.00 hi	58.00 a	15.00 b-d
		120	26.50 i	57.50 a	16.00 bc
		180	27.50 g-i	58.00 a	14.50 c-e
	Poultry manure	0	33.00 b-d	57.50 a	9.50 g
		60	33.50 b-d	57.50 a	9.00 g
		120	28.50 gh	55.50 a	16.00 bc
		180	32.00 de	58.50 a	9.50 g
	Vermicompost	0	30.50 ef	56.00 a	13.50 d-f
		60	32.00 de	56.00 a	12.00 f
		120	29.00 fg	56.50 a	14.50 c-e
		180	28.50 gh	58.00 a	13.50 d-f
	Wheat straw	0	32.50 cd	54.00 a	13.50 d-f
		60	33.00 b-d	54.00 a	13.00 ef
		120	34.00 bc	56.00 a	10.00 g
		180	34.50 b	56.00 a	9.50 g

Table 3. The interaction effects of rainfall, soil amendment type, and time on sand, silt, and clay

Means in the columns followed by the same letter are not significantly different according to LSD test at $P < 0.05$.

Rainfall	Application	Time (day)	Sand (%)	Silt (%)	Clay (%)
Before	**Surface**	0	21.80 a	62.00 a	16.00 a
		60	21.80 a	62.00 a	16.00 a
		120	21.80 a	62.00 a	16.00 a
		180	21.80 a	62.00 a	16.00 a
	Mixture	0	21.80 a	62.00 a	16.00 a
		60	21.80 a	62.00 a	16.00 a
		120	21.80 a	62.00 a	16.00 a
		180	21.80 a	62.00 a	16.00 a
After	**Surface**	0	31.80 a	55.00 d	13.20 a
		60	32.00 a	55.00 d	13.00 a
		120	30.40 a	56.60 b	13.00 a
		180	31.80 a	56.20 bc	12.00 a
	Mixture	0	33.00 a	55.00 d	12.00 a
		60	34.20 a	55.20 cd	10.60 a
		120	32.80 a	53.60 e	13.60 a
		180	33.20 a	56.00 b-d	10.80 a

Table 4. The interaction effects of rainfall, application method, and time on sand, silt, and clay

Means in the columns followed by the same letter are not significantly different according to LSD test at P < 0.05.

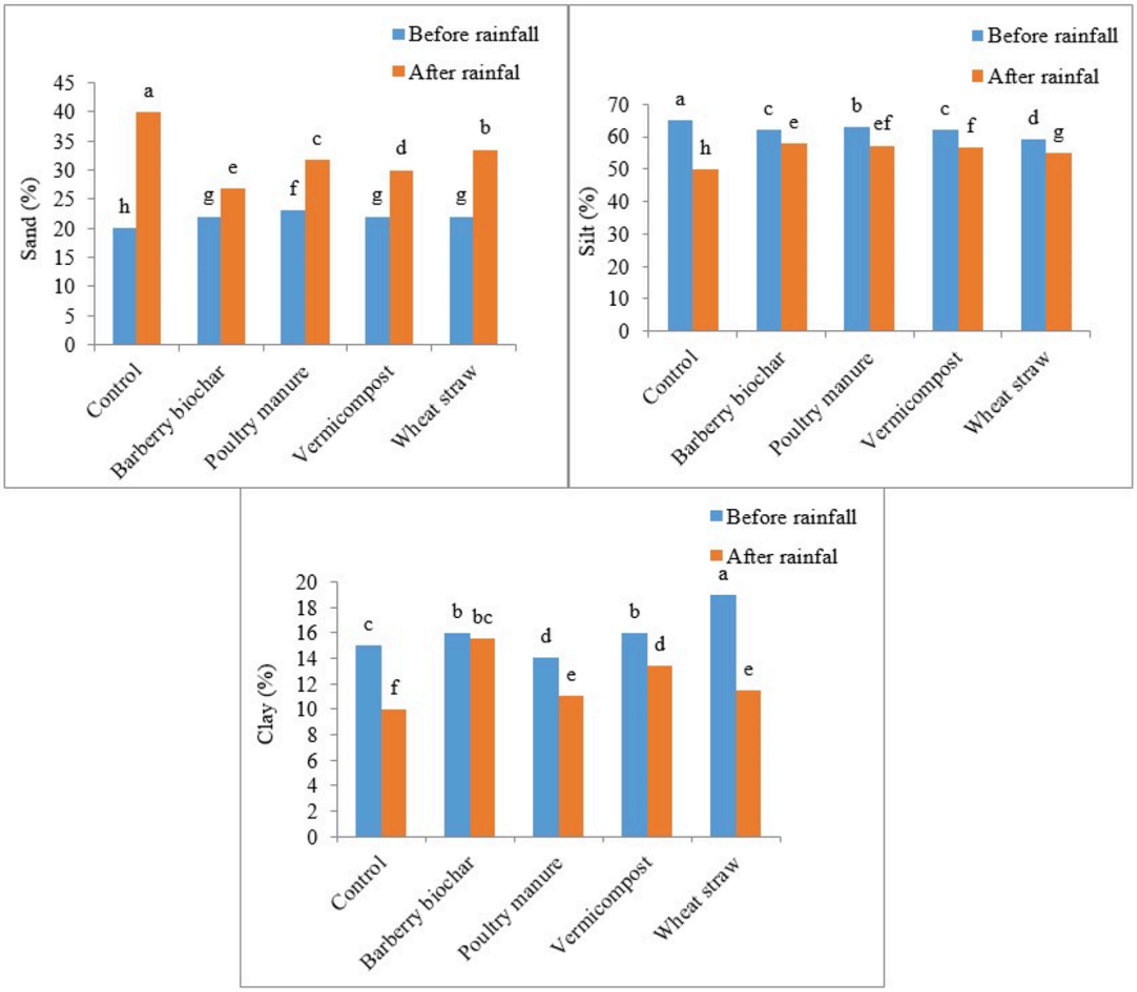

Fig. 5. The interaction effects of rainfall and soil amendment type on sand, silt, and clay

Values followed by the same letter are not significantly different according to the LSD test at P < 0.05

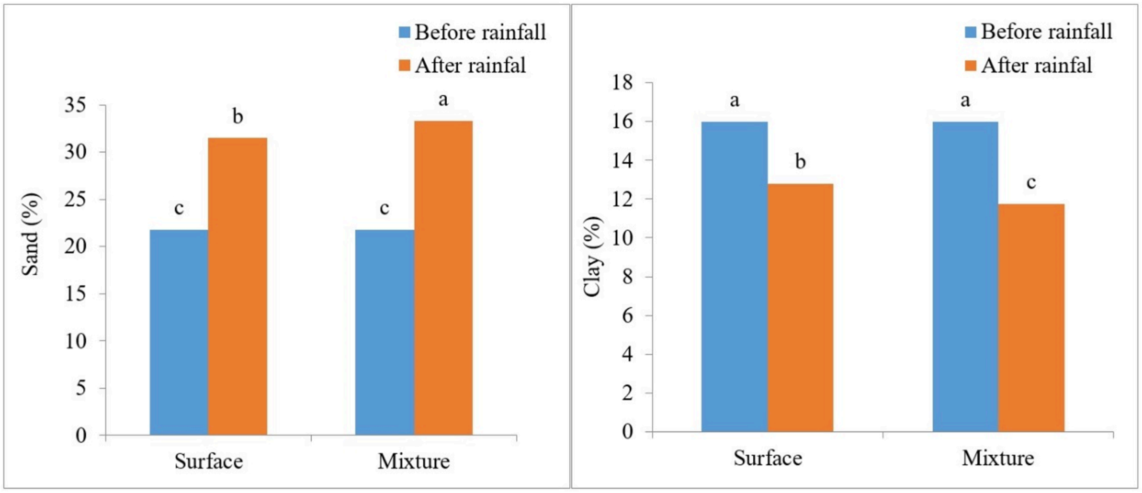

Fig. 6. The interaction effects of rainfall and application method on sand and clay

Values followed by the same letter are not significantly different according to the LSD test at P < 0.05

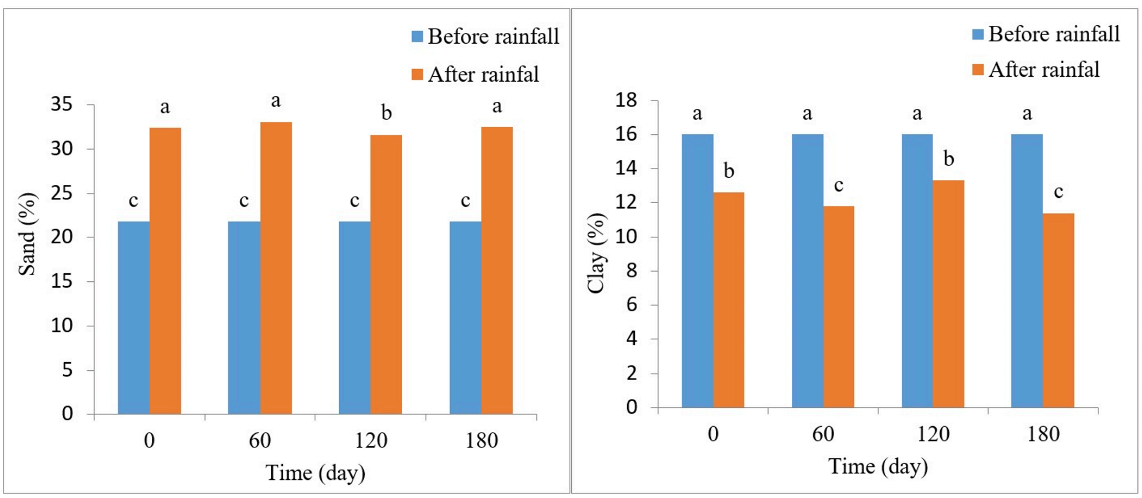

Fig. 7. The interaction effects of rainfall and time on sand and clay

Values followed by the same letter are not significantly different according to the LSD test at P < 0.05

3.3. Fluctuations in parameters associated with the soil erosion process

The analysis of variance table results (Table 5) revealed significant main effects for amendment type, application method, and time at the 1% level across all investigated traits. Additionally, the interaction effects of amendment type × application method and amendment type × time were found to be significant for all traits under examination. Furthermore, the interaction effect of amendment

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application method × time and the interaction effect of amendment type × application method × time were significant for all investigated traits, except for Qs and DWS, at the 1% level. As indicated in Table 6, the mixed method yielded the highest values for Q and runoff duration at zero time, while the surface method at 180 days recorded the lowest values. In terms of the Time to Runoff attribute, the surface method at 180 days exhibited the highest values, whereas the mixed method at zero time showed the lowest values. Additionally, the Runoff coefficient values reached their highest and lowest points at 180 days, with the mixed method yielding the highest values. The control treatments yielded the highest values for Qs, DWS, Q, and runoff duration, while the surface application of barberry biochar resulted in the lowest values. In terms of the time to runoff trait, the highest values were observed with barberry surface application, and the lowest values were associated with the control treatments. Similarly, the highest runoff coefficients were recorded in the control treatments, and the lowest values were linked to the surface application of barberry (Table 7). The maximum and minimum values for the traits of Qs, DWS, Q, and runoff duration were observed in the control treatments and the barberry biochar application, respectively, over a period of 180 days. Regarding the Time to Runoff attribute, the highest and lowest values were recorded in the barberry biochar treatments and the control treatment, respectively, over the 180-day period. The highest and lowest values for runoff coefficient were found in the control treatments and after the application of barberry biochar in 180 days, respectively (Table 8). In Table 9, the individual effects of amendment type, application method, and time on soil erosion properties are reported. The results in this table reveal that following the control treatment, the wheat straw application demonstrated the most significant impact on soil erosion, while the barberry biochar treatment exhibited the least erosion and sedimentation effects. This underscores the efficacy of barberry biochar in reducing runoff, soil erosion, and sedimentation compared to other amendments. Moreover, surface application (mulching) yielded superior results compared to mixed application. Additionally, the 180-day (6-month) duration proved more effective than other time intervals in reducing erosion and sedimentation. Based on the findings outlined in Table 10, the control treatment yielded the highest values for Q and runoff duration, while the lowest values were observed in the surface application of barberry biochar over 180 days. The maximum and minimum values for Time to Runoff were recorded in the surface application treatment of barberry biochar over 180 days and the control treatment, respectively. As for the runoff coefficient, the highest and lowest values were associated with control treatments and the surface application of barberry biochar over 180 days, respectively.

Analysis of variance	Qs	DWS	Q	Runoff duration	Time to runoff	Runoff coefficient
Modifier (M)	611.50**	24932.52 **	10365947.0 **	444909.4 **	106162.6 **	7992.51 **
Application (A)	53.63**	2064.75 **	734952.0 **	31248.1 **	7128.9 **	550.56 **
Time (T)	50.46**	1002.89 **	304198.0 **	14173.7 **	3531.3 **	227.10 **
M × A	6.69**	137.38 **	65964.0 **	2682.8 **	568.4 **	50.69 **
M × T	7.44**	124.92 **	58653.0 **	3665.0 **	782.1 **	44.80 **
A × T	0.85 ns	5.60 ns	5742.0**	336.6 **	67.8 **	3.89 **
M × A × T	0.83 ns	3.10 ns	5379.0**	192.1 **	28.3 **	4.03 **
Error	0.49	4.02	181.0	32.3	6.5	0.06

Table 5. Analysis of variance for the effects of amendment type, application method, and time on the soil erosion properties after applying rainfall

*** and ns: Significance at 1 of probability level and non-significance, respectively*

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Application method	Time (day)	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
Surface	0	35.66 a	86.92 a	2416.00 c	581.20 c	179.40 f	67.10 c
	60	34.04 a	82.19 a	2369.60 d	572.60 d	186.20 d	65.80 d
	120	33.29 a	78.12 a	2282.60 f	553.80 f	194.40 b	63.39 f
	180	32.81 a	76.26 a	2250.00 g	546.60 g	197.60 a	62.48 g
Mixture	0	36.47 a	94.40 a	2567.40 a	613.40 a	164.00 h	71.08 a
	60	35.29 a	90.29 a	2523.00 b	605.40 b	171.00 g	70.07 b
	120	34.37 a	84.85 a	2418.40 c	580.20 c	181.40 e	67.16 c
	180	34.31 a	82.70 a	2351.60 e	567.00 e	187.80 c	65.31 e

Table 6. The interaction effects of application method and time on the soil erosion properties

Means in the columns followed by the same letter are not significantly different according to the LSD test at P < 0.05

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Modifier	Application method	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
Control	Surface	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 i	80.50 a
	Mixture	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 i	80.50 a
Barberry biochar	Surface	29.63 g	40.18 i	1344.25 i	362.25 i	285.00 a	37.33 i
	Mixture	30.52 f	47.86 h	1556.25 h	410.50 h	265.75 b	43.22 h
Poultry manure	Surface	31.82 e	83.13 e	2610.25 d	625.75 d	166.25 f	72.50 d
	Mixture	34.31 c	92.98 c	2708.25 c	647.50 c	154.75 g	75.22 c
Vermicompost	Surface	32.31 e	72.53 g	2240.50 g	528.00 g	202.50 c	62.23 g
	Mixture	33.80 d	80.82 f	2387.75 f	560.25 f	188.00 d	66.05 f
Wheat straw	Surface	34.23 cd	87.41 d	2552.75 e	621.75 e	169.25 e	70.91 e
	Mixture	35.15 b	97.51 b	2773.25 b	659.25 b	147.75 h	77.03 b

Table 7. The interaction effects of amendment type and its application methods on soil erosion properties

Means in the columns followed by the same letter are not significantly different according to the LSD test at $P < 0.05$

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Amendment	Time (day)	Qs (gr/lit)	DWS (gr)	Q (Cm3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
Control	0	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 n	80.50 a
	60	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 n	80.50 a
	120	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 n	80.50 a
	180	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 n	80.50 a
Barberry biochar	0	33.50 ef	56.09 k	1674.50 m	443.50 j	244.50 d	46.51 m
	60	30.24 h	47.95 l	1584.00 n	419.00 k	266.50 c	43.99 n
	120	28.59 i	38.21 m	1334.50 o	354.50 l	290.00 b	37.06 o
	180	27.98 i	33.84 n	1208.00 p	328.50 m	300.50 a	33.55 p
Poultry manure	0	34.16 de	94.31 bc	2759.00 b	648.00 b	154.00 m	76.63 b
	60	33.69 ef	90.63 de	2687.50 cd	643.50 bc	156.50 lm	74.65 c
	120	32.15 ef	84.16 fg	2615.50 g	631.50 d	163.50 j	72.65 g
	180	32.26 g	83.13 g	2575.00 h	623.50 e	168.00 i	71.52 h
Vermicompost	0	35.25 bc	85.90 f	2436.50 i	568.00 f	181.50 h	67.13 i
	60	33.05 f	78.91 h	2385.00 j	559.50 g	188.50 g	66.25 j
	120	32.26 g	72.49 i	2245.00 k	530.00 h	202.50 f	62.35 k
	180	31.66 g	69.39 j	2190.00 l	519.00 i	208.50 e	60.83 l
Wheat straw	0	35.63 b	95.87 b	2688.50 c	647.00 b	154.50 m	74.68 c
	60	34.59 cd	92.60 cd	2675.00 d	643.00 bc	157.50 kl	74.30 d
	120	34.39 d	91.44 de	2657.00 e	639.00 c	159.50 k	73.82 e
	180	34.16 de	89.93 e	2631.00 f	633.00 d	162.50 j	73.08 f

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Table 8. Interaction effects of amendments and time on measured traits

Means in the columns followed by the same letter are not significantly different according to the LSD test at P < 0.05.

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	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
Modifier						
Control	41.76 a	121.20 a	2900.00 a	680.00 a	124.00 e	80.50 a
Barberry biochar	30.07 d	44.02 e	1450.25 d	386.37 e	275.37 a	40.28 d
Poultry manure	33.07 c	88.06 c	2659.25 b	636.62 c	160.50 c	73.86 b
Vermicompost	33.05 c	76.67 d	2314.13 c	544.12 d	195.25 b	64.14 c
Wheat straw	34.69 b	92.46 b	2663.00 b	640.50 b	158.50 d	73.97 b
Application method						
Mulching	33.95 b	80.87 b	2329.55 b	563.55 b	189.40 a	64.69 b
Mixture	35.11 a	88.06 a	2465.10 a	591.50 a	176.05 b	68.40 a
Time						
0	36.06 a	90.66 a	2491.70 a	597.30 a	171.70 d	69.09 a
60	34.66 b	86.24 b	2446.30 b	589.00 b	178.60 c	67.93 b
120	33.83 c	81.48 c	2350.50 c	567.00 c	187.90 b	65.28 c
180	33.56 c	79.48 d	2300.80 d	556.80 d	192.70 a	63.89 d

Table 9. The individual effects of the amendment type, application method, and time on soil erosion properties

Means in the columns followed by the same letter are not significantly different according to the LSD test at P < 0.05;

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Amendment	Application method	Time (day)	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
Control treatment	Mulching	0	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
		60	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
		120	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
		180	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
	Mixture	0	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
		60	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
		120	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
		180	41.76 a	121.12 a	2900.00 a	680.00 a	124.00 u	80.50 a
Barberry biochar	Mulching	0	33.59 a	51.21 a	1524.00 v	412.00 s	257.00 d	42.33 v
		60	29.88 a	43.27 a	1448.00 w	386.00 t	279.00 c	40.20 w
		120	28.01 a	34.88 a	1245.00 y	335.00 v	298.00 b	34.60 y
		180	27.04 a	31.37 a	1160.00 z	316.00 w	306.00 a	32.21 z
	Mixture	0	33.41 a	60.98 a	1825.00 t	475.00 q	232.00 e	50.69 t

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Amendment	Application method	Time (day)	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
		60	30.59 a	52.63 a	1720.00 u	452.00 r	254.00 d	47.78 u
		120	29.17 a	41.54 a	1424.00 x	374.00 u	282.00 c	39.52 x
		180	28.92 a	36.32 a	1256.00 y	341.00 v	295.00 b	34.90 y
Poultry manure	Mulching	0	32.69 a	89.31 a	2732.00 d	638.00 e	160.00 p	75.90 d
		60	32.32 a	85.44 a	2643.00 f	633.00 ef	162.00 op	73.41 f
		120	31.19 a	79.10 a	2536.00 jk	617.00 ij	171.00 k-m	70.44 k
		180	31.10 a	78.69 a	2530.00 k	615.00 ij	172.00 kl	70.27 k
	Mixture	0	35.64 a	99.32 a	2786.00 b	658.00 bc	148.00 rs	77.37 b
		60	35.07 a	95.82 a	2732.00 d	654.00 c	151.00 r	75.88 d
		120	33.11 a	89.23 a	2695.00 e	646.00 d	156.00 q	74.86 e
		180	33.42 a	87.58 a	2620.00 g	632.00 e-g	164.00 o	72.77 g
Vermicompost	Mulching	0	35.24 a	82.55 a	2342.00 n	547.00 m	191.00 i	65.05 n
		60	32.14 a	73.61 a	2290.00 p	539.00 n	198.00 h	63.61 p

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Amendment	Application method	Time (day)	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
		120	31.44 a	68.55 a	2180.00 r	516.00 p	209.00 f	60.55 r
		180	30.42 a	65.41 a	2150.00 s	510.00 p	212.00 f	59.72 s
	Mixture	0	35.26 a	89.26 a	2531.00 k	589.00 k	172.00 kl	69.20 m
		60	33.95 a	84.21 a	2480.00 m	580.00 l	179.00 j	68.89 m
		120	33.08 a	76.43 a	2310.00 o	544.00 mn	196.00 h	64.16 o
		180	32.90 a	73.38 a	2230.00 q	528.00 o	205.00 g	61.94 q
Wheat straw	Mulching	0	35.01 a	90.42 a	2582.00 h	629.00 fg	165.00 no	71.72 h
		60	34.09 a	87.53 a	2567.00 hi	625.00 gh	168.00 mn	71.30 i
		120	34.07 a	86.95 a	2552.00 ij	621.00 hi	170.00 lm	70.89 j
		180	33.76 a	84.75 a	2510.00 l	612.00 j	174.00 k	69.72 l
	Mixture	0	36.24 a	101.32 a	2795.00 b	665.00 b	144.00 t	77.64 b
		60	35.09 a	97.67 a	2783.00 b	661.00 bc	147.00 st	77.30 b
		120	34.72 a	95.94 a	2763.00 c	657.00 c	149.00 rs	76.76 c

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Amendment	Application method	Time (day)	Qs (gr/lit)	DWS (gr)	Q (Cm^3)	Runoff duration (Sec)	Time to runoff (Sec)	Runoff coefficient (%)
		180	34.56 a	95.12 a	2752.00 c	654.00 c	151.00 r	76.44 c

Table 10. Interaction effects of amendment, application method, and time on soil properties following erosion application

Means in the columns followed by the same letter are not significantly different according to the LSD test at P < 0.05

4. Discussion

4.1. Soil erosion dynamics and amendment effects

The results of this study shed light on the complex interplay between soil erosion dynamics and the application of various organic amendments. As highlighted in the introduction, soil erosion poses a significant threat to agricultural sustainability and environmental conservation. The adverse effects of erosion on soil quantity and quality were evident in the alterations observed in sand, silt, and clay percentages. The increased sand content after the rainfall simulator application aligns with findings in arid and semi-arid regions where erosion is often exacerbated due to insufficient organic matter.

The choice of organic amendments, including barberry biochar, vermicompost, poultry manure, and wheat straw, played a pivotal role in influencing soil properties. The efficacy of these amendments in mitigating erosion, demonstrated by reduced runoff coefficients and sediment discharge rates, resonates with findings in similar studies employing organic materials to enhance soil quality.

4.2. Temporal dynamics and application methods

The temporal aspect of the study, with amendments applied at different intervals, offers insights into the temporal effectiveness of organic amendments. The variations observed over time underscore the dynamic nature of soil erosion processes and the need for comprehensive, long-term studies to capture the nuanced impacts of amendments. Notably, the 180-day duration consistently proved more effective in reducing erosion and sedimentation, aligning with the principles of sustained soil management practices.

The comparison of application methods, surface spreading, and complete mixing, introduces an additional layer of complexity. The mixed method, while yielding higher values for parameters like Q and runoff duration at zero time, showcased nuanced variations over the 180-day period. These findings underscore the importance of considering not only the type of amendment but also the application method and duration to optimize erosion control strategies.

4.3. Barberry biochar: a novel amendment strategy

The specific focus on barberry biochar, derived from plant residues generated during the pruning of barberry plants, adds a novel dimension to the study. As outlined in the literature review, biochar has demonstrated soil-enhancing properties, and its application has shown promise in reducing soil erosion. The results of this study reinforce the potential of barberry biochar in significantly mitigating erosion effects, presenting a valuable and locally available organic amendment.

4.4. Implications for sustainable agriculture and resource management

The findings of this study hold significant implications for sustainable agriculture, especially in regions like South Khorasan Province, where barberry production is a major economic activity. The utilization of barberry residues for biochar production not only addresses the challenge of agricultural waste management but also contributes to soil conservation efforts. The positive impact on soil physicochemical properties further highlights the multifaceted benefits of such organic amendments in enhancing overall soil fertility.

4.5. Limitations and future directions

While the study provides valuable insights, certain limitations must be acknowledged. The experimental setup, though comprehensive, represents a specific geographic location and climatic conditions. Generalizing the findings to other regions warrants caution. Future research could explore the scalability of barberry biochar application across diverse environments and assess its economic feasibility on a larger scale.

4.6. Comparative analysis with reference review

4.6.1. Organic amendments and soil erosion: insights from literature

The results obtained in this study align with and extend the findings reported in the literature review. As discussed in the reference section, soil erosion is a global concern with far-reaching implications for agriculture and environmental sustainability. The observed reduction in runoff coefficients and sediment discharge rates with the application of organic amendments echoes the outcomes of previous studies (Biddoccu et al., 2020; Chellappa et al., 2021).

The specific choice of organic amendments in our study, including barberry biochar, vermicompost, poultry manure, and wheat straw, mirrors the diversity of materials explored in existing research (Gholami et al., 2014; Wang et al., 2017; Farhoodi et al., 2019). Our results support the notion that the type of organic amendment significantly influences soil properties and erosion resistance, reinforcing the importance of tailored soil management strategies (Siedt et al., 2021).

4.6.2. Temporal dynamics and long-term impact

The temporal dynamics observed in this study provide nuanced insights into the evolution of soil erosion properties over time. While short-term studies have their merits, our 180-day investigation adds depth to the understanding of how amendments interact with soil properties in the medium term. These findings corroborate the assertions made in the literature review regarding the necessity for comprehensive, time-sensitive analyses (Doam et al., 2015; Shabanpour et al., 2021).

Moreover, the consistent effectiveness observed at the 180-day mark underscores the importance of prolonged contact between amendments and soil. This aligns with existing literature highlighting the need for sustained intervention strategies to ensure lasting improvements in soil fertility and erosion resistance (Chen et al., 2018; Siedt et al., 2021).

4.6.3. Barberry biochar as a novel amendment strategy

Our emphasis on barberry biochar as a locally sourced organic amendment introduces a novel dimension to the discussion. While various studies have explored the potential of biochar derived from different sources, the use of barberry residues represents a unique and region-specific approach. The success of barberry biochar in reducing erosion, as evidenced in our results, resonates with the idea that locally available organic materials can offer effective and sustainable solutions to soil management challenges (Vahidi et al., 2022).

4.6.4. Implications for sustainable agriculture and resource management: bridging theory and practice

The study's findings hold immediate implications for the region of South Khorasan Province, a major barberry-producing area. By utilizing barberry residues for biochar production, we not only address agricultural waste management but also introduce a practical and sustainable approach to soil conservation. This practical application of theoretical knowledge aligns with the overarching goals of sustainable agriculture (Pimentel and Burgess, 2013; Scotti et al., 2015).

4.6.5. Limitations and future research directions: a call for contextual adaptation

It is crucial to acknowledge the study's limitations when comparing results with the reference section. Our research, while comprehensive, is geographically specific to the South Khorasan Province. Generalizing findings to other regions requires careful consideration of local climatic and soil conditions. Future research endeavors should aim for a broader geographical scope to assess the adaptability and scalability of the proposed organic amendment strategies.

5. Conclusion

This study contributes valuable insights into soil erosion dynamics, the efficacy of organic amendments, and the unique potential of barberry biochar in mitigating erosion effects. The comprehensive exploration of various organic amendments, including vermicompost, poultry manure, wheat straw, and the region-specific barberry biochar, elucidates their role in enhancing soil properties and reducing erosion. The comparison of application methods, surface spreading, and complete mixing, adds depth to the understanding of how the mode of amendment incorporation influences soil erosion resistance. The temporal dynamics revealed over the 180-day duration underscore the importance of sustained soil management practices for lasting improvements in soil fertility and erosion control. Our findings align with existing literature, affirming the positive impact of organic amendments on reducing runoff coefficients and sediment discharge rates. The emphasis on barberry biochar as a locally sourced and effective organic amendment introduces a novel strategy for sustainable agriculture, particularly in barberry-producing regions. The practical implications of this research extend to South Khorasan Province, where the utilization of barberry residues for biochar production offers a dual benefit of waste management and soil conservation. However, acknowledging the study's limitations, generalizing these findings requires caution, urging future research to explore the adaptability of these strategies in diverse geographic and climatic contexts. In summary, this study not only advances the theoretical understanding of soil erosion dynamics and organic amendments but also provides tangible insights for practitioners and policymakers seeking sustainable solutions for soil management in agricultural landscapes. The synthesis of theoretical knowledge and practical application is essential for shaping effective strategies that promote environmental resilience and agricultural sustainability.

Statements and Declarations

Conflict of Interest

The authors declare the absence of any identifiable conflicting financial interests or personal relationships that could be perceived as influencing the findings presented in this paper.

Data Availability

Access to the data will be provided upon request.

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