

Unlocking the Sheet and Splash Erosion Mitigation Effects of Engineered Porous Biochar Across Slope Gradients in an Agricultural Loess Soil

Seyed Hamidreza Sadeghi

sadeghi@modares.ac.ir

Tarbiat Modares University

Sudabeh Gharemahmudli

Tarbiat Modares University

Somayeh Zare

Tarbiat Modares University

Padideh Sadat Sadeghi

Tarbiat Modares University

Habibollah Younesi

Tarbiat Modares University

Fengbao Zhang

Northwest A&F University

Mahboubeh Mirzahosseini

Tarbiat Modares University

Yahya Parvizi

Soil Conservation and Watershed Management Research

Mehdi Homaee

Tarbiat Modares University

Shen Nan

Northwest A&F University

Yao Li

Shanghai Jiao Tong University

Article

Keywords: Distributed Erosion, Drop Erosion, Erosion Management, Engineered Biochar, Soil Conservation

Posted Date: October 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11109701/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Loess soils are among the most sensitive soil units to erosion due to their self-degrading nature and inherent porosity. Biochar amendments change soil properties and affect soil erosion. However, the effects of Modified Genetic Porous Carbon (MGPC) on sheet Erosion and runoff remain unknown. This study aimed to quantify MGPC's effectiveness in reducing erosion rates and controlling surface soil degradation in a laboratory study under simulated rainfall conditions. We conducted experiments on three slopes (8, 15, and 27%), with five biochar treatments applied at 1, 3, and 5% by weight, under a constant rainfall intensity of 70 mm h^{-1} . We measured erosion processes, including soil loss, sediment concentration, and splash, over 30 min with three replicates. The findings showed that adding MGPC significantly ($p < 0.05$) modulated sheet Erosion processes. The results indicated that the 5% by weight treatment performed best in reducing soil loss rate, sediment concentration, and splash erosion, suggesting a key role for the modifier in increasing soil surface resistance to raindrop kinetic energy. Meanwhile, MGPC derived from straw, sawdust, palm pruning, and vineyard pruning reduced soil loss by 91%, 71%, 85%, and 70%, respectively, compared to the control treatment at the highest application level (1500 g m^{-2}) and the lowest slope (8%). Analysis of runoff distribution in gutters also indicates a significant reduction in erosion components with MGPC. Overall, all treatments were more effective at higher application rates and on gentler slopes, indicating the strong potential of advanced amendment materials to manage and control water erosion. This research shows that biochar engineering is an efficient conservation technology for managing soil erosion in loess farmlands and can be proposed and used to restore damaged ecosystems and reduce sediment transport to watersheds.

Introduction

The global challenge of soil erosion, especially in loess soils, has emerged as a major threat to terrestrial ecosystem services, agricultural sustainability, and food security. Loess soils are widely distributed worldwide, especially in arid and semi-arid regions such as Central and West Asia, and constitute approximately one-tenth of the Earth's surface area (Nan et al., 2026). Because of their structure and mechanical instability under the kinetic energy of precipitation, these soils are among the most vulnerable to water and splash erosion (Sharma et al., 2024).

Soil erosion is a natural process that can be exacerbated by steep slopes, high rainfall intensity, and poor land use management, leading to loss of topsoil and essential nutrients, degradation of water quality, and reduced agricultural productivity (Wang et al., 2022; Sharma et al., 2024; Pansak et al., 2026). Soil erosion processes involve the sequential steps of soil detachment, sediment transport, and deposition (Tucker et al., 1997). Understanding the soil detachment process—the detachment of particles from the soil matrix by rainfall and surface runoff—is essential for the accurate modeling and analysis of soil erosion (Govers et al., 1990; Li et al., 2025). Annual erosion destroys about 24 billion tons of the world's fertile topsoil, representing a significant global loss of soil (Abdel Rahman, 2023). Therefore, effective erosion-control measures and sustainable soil-conservation practices are needed. This is necessary to reduce the adverse environmental and socio-economic consequences of soil erosion. Various sustainable measures have been developed to control and reduce soil erosion to maintain soil fertility, increase ecosystem stability, and promote sustainable land management practices. In recent years, biochar, as a new type of soil amendment, has played a positive role in improving soil quality in degraded lands and is known as the "black gold" of degraded soil (Sadeghi et al., 2020a and 2020b; Alfei and Pandoli, 2024). To achieve sustainable development goals and within the framework of circular economy principles, converting biomass waste into biochar through pyrolysis has been proposed as a two-pronged solution for waste management and the sustainable improvement of soil physical and hydraulic properties (Sadeghi et al., 2026b). Biochar, a carbon-rich material produced by pyrolyzing organic matter, has emerged as a sustainable solution to soil erosion within the framework of the United Nations Sustainable Development Goals (SDGs) (Singh et al., 2025). Biochar addition can change soil porosity, soil bulk density, water retention, infiltration performance, shear strength, fine particle stability, soil pH, cation exchange capacity, and other physical and chemical properties (Verheijen et al., 2019; Obia et al., 2020; Saffari et al., 2021; Islam et al., 2021) and improve the species and quantity of soil microorganisms (Xu et al., 2020; Zhang et al., 2020). Biochar improves soil structure and properties by integrating physical, chemical, and biological aspects (Luo et al., 2017), thereby achieving positive effects such as increasing infiltration and storage, reducing runoff and sediment, conserving water and soil storage, and increasing fertilizer use and production. As a result, biochar is considered a valuable tool to prevent soil and runoff loss (Yu et al., 2021). Therefore, this method provides an effective way to use soil and water resources efficiently in arid and semi-arid regions.

Modification techniques are commonly used to improve biochar adsorption efficiency. A more advanced approach in recent years is engineered biochar, i.e., biochar designed for a specific functional purpose through processes such as surface modification, physical or chemical activation, loading with specific elements or compounds, adjusting pyrolysis temperature, or incorporating polymers and stabilizing agents. This approach transforms biochar from a general soil amendment into a targeted material for controlling erosion, increasing particle adhesion, enhancing the formation of stable soil aggregates, and reducing the soil surface's sensitivity to rainfall. On the other hand, using biowastes to produce engineered biochar not only reduces the volume of landfilled waste and prevents greenhouse gas emissions from natural decomposition, but also provides a platform for returning carbon to the soil cycle. By optimizing the structural and physicochemical properties of biochar, this process not only creates a porous material with high absorption capacity and a large specific surface area but also makes it an efficient agent for stabilizing soil aggregates and modulating surface hydrological behavior in loess soils.

Sheet erosion, one of the most important challenges in land management, not only causes physical soil loss and reduces the thickness of fertile horizons but also affects the quality of downstream water resources by increasing sediment concentration in runoff. In sheet Erosion under simulated rain conditions, splashing acts as a catalyst, greatly increasing suspended sediment concentration in runoff by releasing fine particles (silt and clay). Therefore, controlling this process means not only reducing erosion at the source but also managing the sediment load and slowing the transport of contaminants bound to sediment. Understanding the precise mechanisms by which this material interacts with loess soil under simulated rainfall conditions, particularly regarding surface and splash erosion across different slopes, remains a knowledge gap. The present study aims to fill this gap by evaluating the performance of this modifier at different levels on different slopes in reducing soil loss and splash erosion. Therefore, the main objective of this study is to evaluate the effect of engineered biochar on reducing soil loss and managing sediment concentration on loess soil surfaces, providing a new solution for promoting ecological sustainability in sensitive lands.

Materials and Methods

Engineered Biochar Preparation

Genetically modified porous carbon is a porous, carbon-rich, and fine-grained material that is produced by two main methods of physical or chemical activation at a temperature of about 800°C in an oxygen-free environment. To produce genetically modified porous carbon, researchers first produced primary biochar from biomass sources such as agricultural residues, industrial biowastes, and wood waste (Zhang et al., 2004). For this purpose, in the first stage, after collection, the raw materials prepared from agricultural (straw and stubble), horticultural (palm and vineyard pruning), and industrial (sawdust and tissue paper production waste) wastes were dried and cleaned to reduce moisture and remove impurities. We then carried out the main biochar production process, pyrolysis (thermal decomposition), under low-oxygen conditions at about 400°C (Sadeghi et al., 2026a, b).

After initial biochar preparation, we produced genetically modified porous carbon from the optimized samples. For this purpose, we chemically activated the biochar with potassium hydroxide (KOH) at a 1:1 ratio at about 800°C in an oxygen-free environment. We produced each sample by mixing an equal ratio of initial biochar to KOH with the required amount of water. After mixing, we dried the solution for a specified time (depending on the sample) at about 120°C. Then, we pyrolyzed the samples in a furnace under a nitrogen gas flow for about 2 hours at 800°C (Zhang et al., 2021; Kumar et al., 2025; Sadeghi et al., 2026a, b).

After 24 hours, the temperature decreased, and the samples in the tank and tray were removed from the furnace, ground, and pounded. After completing these steps, the samples should have been washed with distilled water until their pH reached neutrality. However, this step was not performed because it requires high water consumption to reach neutrality and is not used under natural conditions. Among the investigated feedstocks, straw, sawdust, palm-pruning residues, and vineyard-pruning residues were successfully converted into engineered porous biochar through KOH activation. We first converted tissue-paper production waste to primary biochar and characterized it for comparison. Because the tissue-paper-derived biochar exhibited a high inorganic/ash fraction (more than 80% lime-like residues) during the activation process, it was not subjected to KOH activation. Therefore, we did not classify it as an engineered porous biochar. Nevertheless, we retained the conventional tissue-paper-derived biochar in the rainfall simulation experiments as a comparative treatment to evaluate the performance of activated porous biochar relative to a non-activated biochar (Fig. 1d). Figure 1 shows the steps for preparing genetically modified porous carbon in a thermal furnace and the resulting samples.

Figure 1

Experimental Setup

The soil used in this study was collected from the Kechik agricultural Region in eastern Golestan Province. This region is characterized by loess sediments and fine-grained deposits that influence the geomorphology. These sediments have developed in many places as loess layers with a relatively loose structure, high porosity, and high erosion susceptibility. Because of their high silt content, low particle cohesion, and low structural stability, loess soils are highly vulnerable to raindrop impact and runoff; under heavy rainfall, they quickly collapse structurally and transport particles. The region's location, its presence on slopes and variable terrain, and the high sensitivity of surface sediments to separation and transport make it prone to water erosion. The study area has mainly sloped to moderately sloping terrain, and elevation changes, along with surface flow patterns and runoff concentration, play an important role in intensifying erosion processes. The region has a temperate-to-cold, semi-arid climate. The average annual rainfall in the region is about 482 mm. The rainfall pattern in this region is mainly characterized by short-term, high-intensity events during some periods of the year, which can increase sheet Erosion, especially on lands with poor surface cover.

To conduct this research, we collected soil samples from the surface layer (0–20 cm depth) of the study area. After collection, we placed the samples in special bags and transported them to the Rainfall and Erosion Simulation Laboratory of Tarbiat Modares University, Iran. In the laboratory, we first dried the samples at ambient temperature and, after crushing the clumps, passed them through a 2-mm sieve to obtain uniform soil for the experiments (Sadeghi et al., 2021).

We conducted the experiments in small erosion plots filled with loess soil. We chose loess soil because of its high susceptibility to erosion, rapid structural degradation under raindrop impact, and suitability for investigating the effects of organic and inorganic amendments on particle separation. Each small erosion plot measured 0.50 × 0.50 m and had a total depth of approximately 0.30 m. A layer of mineral pumice, approximately 15–20 cm thick, was placed at the bottom of each plot, overlaid by approximately 10–12 cm of homogenized loess soil. We thoroughly mixed the prescribed amount of biochar manually with the entire loess soil plow layer to ensure homogeneous incorporation throughout the experimental soil depth. Thus, we incorporated the biochar into the soil matrix rather than applying it as a surface mulch or protective cover. To measure splash erosion, we installed two splash gutters a few centimeters above the soil surface, covering about 14% of the total area of the treated and control plots (Sadeghi and Parvizi, 2022).

The experimental treatments included five biochar materials: four engineered porous biochars derived from straw, sawdust, palm-pruning residues, and vineyard-pruning residues, and one conventional, non-activated biochar derived from tissue-paper waste. The experimental treatments included three porous-carbon levels at 1, 3, and 5% by weight relative to the soil (w/w). We evaluated the treatments under three slope gradients (i.e., 8, 15, and 27%), with three independent replicates for each treatment–slope combination. After biochar incorporation, we maintained the prepared plots under ambient laboratory conditions for four days before the rainfall simulation experiments. During this period, we protected the plots from external rainfall while allowing the soil–biochar mixtures to equilibrate under laboratory ambient conditions. Immediately before each rainfall simulation, we positioned the plots at the prescribed slope and subjected them to the standardized rainfall event.

We applied artificial precipitation using a rain simulator under controlled laboratory conditions. To determine the components of the experimental rainfall, rainfall statistics and intensity, duration, and frequency curves of the Kechik synoptic station, as the closest synoptic station to the study area, were used as provided in Fig. 2. Accordingly, a rainfall intensity of about 70 mm h^{-1} was considered the design rainfall and was proportional to the prevailing rainfall in the area, and the duration of the rainfall was also considered, taking into account the design rainfall duration and uniformity of other conditions in all experimental plots; ultimately, 30 min and a rainfall volume of 8.75 L (Sadeghi et al., 2021).

Figure 2

In each rain-simulation series, erosion plots were placed on sloping surfaces at 8, 15, and 27 percent, as determined by the desired slopes in the rain and erosion simulator laboratory. To assess precipitation uniformity, we also calculated the Christensen uniformity coefficient (Christiansen, 1942). Thus, all experiments used a mean rainfall intensity of 70 mm h^{-1} and a uniformity coefficient of $94.241 \pm 0.697\%$.

We collected sediments from each control and treated plot outlet in sampling containers every 2 minutes. To estimate soil loss, the collected samples were left to stand for 24 h (Sadeghi et al., 2023), and after draining excess water from the samples, the remaining sediment was transferred into appropriate containers with a certain weight and then placed in a hot oven at 105°C for 24 h until dry and weighed using a balance (Mumzaei et al., 2026).

To measure splash erosion, after the rain simulation at each experimental stage, samples collected from the two splash gutters (right and left) were left stationary for 24 h to allow sediment to settle, and water was then slowly drained onto the settled sediment. We poured the sediment samples, along with excess runoff, into metal containers of known weight and dried them in a thermal oven at 105°C for 24 h. We then weighed the dried sediment samples using digital scales (Gharemahmudli et al., 2023). We ultimately analyzed the effects of slope and different levels of porous carbon on these variables. This laboratory approach, with its controlled and repeatable conditions, allowed a precise assessment of how soil amendments reduce the susceptibility of loess soils in the region to water erosion.

Statistical Analyses

After running three replicates for each treatment, sheet Erosion and splash soil loss data were collected and summarized using Microsoft Excel 2019 software, and the mean values with standard deviation were calculated. To perform statistical comparisons, we first assessed data normality and equality of variances using the Shapiro-Wilk and Levene's tests (Shapiro et al., 1965). We then used a repeated-measures general linear model (GLM) to compare surface, treatment, and slope soil loss across rainfall events. First, we examined a three-way analysis of variance test, then a two-way analysis of variance, and finally a one-way analysis of variance. To compare means, we used the Duncan test to facilitate graphical comparison of statistical results, show minor differences, and select the best treatment or treatments. We performed all statistical analyses in SPSS Statistics 26.0, and prepared figures in Origin 2024.

Results and Discussion

Effect of Porous Biochar on Sheet Erosion

The results of measuring the total soil loss and sediment concentration of small erosion plots with two-minute sample collection intervals in the defined and control treatments, at three levels of 1, 3, and 5% by weight (i.e., 300, 900, and 1500 g m^{-2}) and three slopes of 8, 15, and 27%, and with three replications, are presented in Tables 1 and 2, and Fig. 3, with their comparative distribution results.

Table 1

Total soil loss values (g) from experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from various raw materials at different slopes (i.e., 8, 15, and 27%)

Raw material	Plot number and descriptive statistics	Control			300			900			1500		
		8	15	27	8	15	27	8	15	27	8	15	27
Vineyard pruning	1	11.19	17.88	13.72	8.10	20.05	11.31	3.11	10.95	4.55	6.85	14.56	17.44
	2	12.89	17.92	12.33	8.00	22.19	8.31	3.89	12.38	4.90	1.59	14.29	20.29
	3	13.08	19.03	13.03	7.73	21.83	5.23	4.93	12.30	4.71	2.91	12.53	17.11
	Mean	12.72	18.28	13.03	7.94	21.36	8.28	3.98	11.88	4.72	3.78	13.79	18.28
	Standard Deviation	1.38	0.65	0.70	0.19	1.15	3.04	0.92	0.81	0.17	2.74	1.11	1.75
	Coefficient of Variation (%)	10.88	3.55	5.36	2.41	5.38	36.74	23.05	6.81	3.69	72.34	8.01	9.55
Palm pruning	1	13.04	11.43	9.69	8.89	10.18	12.15	4.55	7.66	10.85	2.35	2.38	2.08
	2	12.94	11.02	10.19	7.92	10.35	13.22	5.17	8.51	11.82	1.65	3.07	5.73
	3	14.61	12.02	11.09	8.14	9.75	13.69	6.56	10.73	17.06	1.81	2.66	2.93
	Mean	13.53	11.49	10.32	8.32	10.09	13.02	5.43	8.97	13.25	1.94	2.71	3.58
	Standard Deviation	0.94	0.50	0.71	0.51	0.31	0.79	1.03	1.59	3.34	0.37	0.35	1.91
	Coefficient of Variation (%)	6.94	4.39	6.86	6.11	3.11	6.08	18.97	17.70	25.20	19.03	12.82	53.37
Sawdust	1	7.53	10.19	10.65	6.08	9.33	9.23	7.94	8.64	9.09	4.04	4.20	4.57
	2	7.80	8.34	10.68	6.88	8.78	10.22	9.28	10.45	10.95	3.62	3.94	4.29
	3	9.33	9.89	11.48	7.21	9.46	9.35	9.13	11.09	11.33	3.35	3.93	4.31
	Mean	8.22	9.47	10.93	6.72	9.19	9.60	8.78	10.06	10.46	3.67	4.02	4.39
	Standard Deviation	0.97	0.99	0.47	0.59	0.36	0.54	0.74	1.27	1.20	0.34	0.15	0.16
	Coefficient of Variation (%)	11.76	10.48	4.32	8.70	3.90	5.66	8.40	12.65	11.45	9.40	3.83	3.60
Rice straw	1	7.75	8.52	14.98	5.42	5.61	9.09	3.95	4.90	8.27	1.38	1.69	2.23
	2	6.95	10.32	18.07	4.49	5.42	10.01	3.31	4.17	6.97	0.76	2.29	3.94
	3	7.41	8.76	13.76	4.19	5.48	9.40	4.16	4.01	6.98	0.96	1.73	2.32
	Mean	7.37	9.20	15.60	4.70	5.50	9.50	3.81	4.36	7.41	1.03	1.90	2.83
	Standard Deviation	0.40	0.97	2.22	0.64	0.10	0.47	0.44	0.47	0.75	0.32	0.33	0.96
	Coefficient of Variation (%)	5.44	10.58	14.22	13.58	1.76	4.90	11.63	10.78	10.07	30.62	17.58	34.06
Tissue factory	1	8.88	12.48	17.59	6.27	10.74	17.98	3.02	7.21	6.25	2.46	3.70	4.92
	2	6.24	11.50	16.22	3.97	10.35	14.15	3.19	8.32	12.31	3.90	3.35	3.16
	3	6.36	11.75	15.37	7.10	10.07	24.58	3.90	9.12	12.86	7.54	5.42	6.17
	Mean	7.16	12.03	16.39	5.78	10.39	18.90	3.37	8.22	10.47	4.63	4.15	4.75
	Standard Deviation	1.49	0.71	1.12	1.62	0.33	5.28	0.47	0.96	3.67	2.62	1.11	1.51
	Coefficient of Variation (%)	20.87	5.92	6.82	28.08	3.21	27.91	13.80	11.67	35.03	56.47	26.63	31.76

Table 2

Total soil sediment concentration values (g mL⁻¹) from experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from various raw materials at different slopes (i.e., 8, 15, and 27%)

Raw material	Plot number and descriptive statistics	Control			300			900			1500		
		8	15	27	8	15	27	8	15	27	8	15	27
Vineyard pruning	1	13.76	15.13	10.79	12.98	23.77	13.44	8.92	15.68	6.90	15.16	23.29	25.64
	2	14.26	13.97	8.25	11.19	28.13	8.56	7.20	24.67	8.04	12.14	32.84	25.02
	3	28.08	13.86	7.27	19.75	40.63	6.17	6.75	18.82	9.16	6.55	22.76	26.40
	Mean	18.70	14.32	8.77	14.64	30.84	9.39	7.62	19.73	8.03	11.28	26.30	25.69
	Standard Deviation	8.13	0.70	1.82	4.51	8.75	3.70	1.14	4.56	1.13	4.37	5.67	0.69
	Coefficient of Variation (%)	43.46	4.90	20.71	30.84	28.37	39.46	14.97	23.13	14.12	38.72	21.57	2.69
Palm pruning	1	13.11	8.85	10.99	13.55	16.55	19.26	8.87	8.95	11.30	9.07	5.90	2.63
	2	12.85	10.15	11.69	17.89	10.65	21.55	8.74	8.19	29.90	7.27	8.34	9.71
	3	13.87	12.04	9.57	11.35	13.11	16.74	8.21	10.78	21.51	4.86	6.39	3.98
	Mean	13.28	10.35	10.75	14.26	13.44	19.18	8.61	9.31	20.91	7.07	6.88	5.44
	Standard Deviation	0.53	1.61	1.08	3.33	2.96	2.41	0.35	1.33	9.32	2.11	1.29	3.76
	Coefficient of Variation (%)	3.98	15.51	10.04	23.35	22.04	12.54	4.06	14.32	44.58	29.88	18.79	69.07
Sawdust	1	6.88	7.40	8.27	7.80	11.71	7.17	11.75	14.33	9.94	8.84	10.25	6.58
	2	6.58	7.06	8.42	11.70	21.39	8.03	15.83	18.54	11.09	20.38	10.76	5.96
	3	7.20	8.71	8.07	15.24	23.54	8.23	14.72	17.83	11.28	14.89	6.72	6.08
	Mean	6.89	7.72	8.25	11.58	18.88	7.81	14.10	16.90	10.77	14.70	9.24	6.21
	Standard Deviation	0.31	0.87	0.17	3.72	6.30	0.56	2.11	2.26	0.72	5.77	2.20	0.33
	Coefficient of Variation (%)	4.50	11.32	2.07	32.16	33.38	7.20	14.96	13.35	6.73	39.27	23.84	5.30
Rice straw	1	7.00	7.75	9.26	9.64	7.35	10.24	7.26	5.03	9.85	9.25	3.42	3.70
	2	6.10	10.02	15.23	9.46	6.54	18.40	5.99	3.99	6.07	6.58	5.43	12.32
	3	10.84	8.18	12.17	7.49	8.20	10.23	9.39	3.36	5.58	7.60	3.76	4.01
	Mean	7.98	8.65	12.22	8.86	7.36	12.96	7.55	4.13	7.17	7.81	4.20	6.68
	Standard Deviation	2.52	1.21	2.99	1.19	0.83	4.71	1.72	0.85	2.34	1.35	1.08	4.89
	Coefficient of Variation (%)	31.56	13.99	24.43	13.45	11.28	36.38	22.76	20.49	32.62	17.25	25.62	73.20
Tissue factory	1	8.72	13.05	13.74	10.24	24.45	21.30	5.21	9.12	9.81	10.56	10.98	8.15
	2	7.19	10.51	11.83	5.21	14.74	13.61	4.10	7.52	15.27	7.40	5.04	5.00
	3	5.60	7.92	9.76	8.93	10.94	21.73	6.06	13.16	13.63	15.94	10.82	9.62
	Mean	7.17	10.49	11.78	8.13	16.71	18.88	5.13	9.93	12.90	11.30	8.95	7.59
	Standard Deviation	1.56	2.56	1.99	2.61	6.97	4.57	0.98	2.91	2.80	4.32	3.39	2.36
	Coefficient of Variation (%)	21.70	24.40	16.92	32.11	41.68	24.19	19.19	29.26	21.70	38.22	37.85	31.10

Table 1

Table 2

Figure 3

Based on Tables 1 and 2, the mean soil loss across treatments indicates that as porous biochar levels increase, the rate of soil loss decreases. This trend shows that biochar, especially at 1500 g m⁻², significantly reduced surface soil erosion. The standard deviation also indicates greater stability in the biochar treatments. In the control treatment, the standard deviation is higher than in the 1500 g m⁻² treatment, indicating that biochar use increases uniformity in soil loss rates. In other words, soil with the additive shows more stable, resistant behavior under raindrop impact. From a physical perspective, the reduction in soil loss with porous biochar can be attributed to improved soil hydraulic and physical properties. Porous biochar, due to its high porosity, increases the water absorption capacity and improves the permeability of the soil (Sadeghi et al., 2026b). Because the biochar was incorporated into the soil matrix rather than applied as a surface cover, its erosion-mitigation effect is more plausibly related to changes in soil hydraulic behavior. The interconnected pore structure of engineered biochar can provide additional microsites for water storage and modify the hydraulic connectivity of the amended soil (Sadeghi et al., 2026b).

These changes may increase the proportion of rainfall that enters and is temporarily retained within the soil profile, thereby reducing the volume and transport capacity of surface runoff (Sadeghi et al., 2026a). Consequently, sediment detachment and transport may decline even when aggregate stability changes are limited. These findings are consistent with Shi et al. (2022), who reported that adding biochar derived from agricultural residues reduced runoff and soil erosion on sloping lands in China. A study by Abel et al. (2013) also showed that biochar, while increasing permeability, reduced soil loss by 65% in rain simulation experiments. Importantly, the mechanism underlying the observed reduction in soil loss in the present experiment should not be interpreted as a simple surface-cover effect. Unlike mulch-type applications, in which biochar particles remain on the soil surface and directly intercept raindrop impact, all biochar materials in the present study were manually and homogeneously incorporated throughout the approximately 10–12 cm loess soil plow layer. Therefore, the reduction in splash and sheet erosion cannot be attributed solely to physical shielding of the soil surface. Instead, the results suggest that incorporated biochar modified soil–water interactions and the hydraulic response of the soil matrix. The porous structure of the engineered biochar may have increased local water storage and altered infiltration and runoff partitioning, thereby reducing the amount and erosive efficiency of overland flow available for sediment detachment and transport. This interpretation is consistent with recent evidence that biochar's effects on runoff and erosion depend on biochar properties, application rate, soil texture, and rainfall conditions, rather than being universally linked to improved aggregate stability.

In contrast, Liu et al. (2018) noted that biochar application increased soil aggregate stability and significantly reduced suspended solids in runoff. The present results also confirm that porous biochar, especially at higher concentrations, plays an important role in controlling soil loss. Overall, the results show that adding higher levels of porous biochar not only reduces soil loss but also increases the soil system's stability against erosive forces.

Table 1 shows total soil loss values (g) for an 8% slope in the study treatments. In the vineyard pruning waste treatment, increasing the biochar amount from 300 to 900 g m⁻² significantly reduced soil loss. However, at the 1500 g m⁻² level, the mean loss was almost the same as at the 900 g m⁻² level. This indicates that excessive biochar on low slopes does not further improve soil loss and may even stabilize it due to surface accumulation and reduced penetration. The difference was about 50% compared to the control (Fig. 3).

Palm pruning showed that the loss decreased with increasing biochar levels from 300 to 900 g m⁻², reaching a minimum at 1500 g m⁻². The fibrous and coarse structure of palm waste increased surface porosity and reduced runoff. In this treatment, the mean soil loss decreased by about 80%. Lee et al. (2015) further confirm this finding, showing that applying biochar can reduce soil loss by at least 60%. In the sawdust residue treatment, loss was highest at 900 g m⁻², then decreased to 300 g m⁻², and further decreased at 1500 g m⁻². The finer-particle-size sawdust at the medium biochar level likely closed soil pores, reducing infiltration. However, at the higher level (1500 g m⁻²), runoff decreased because increased organic matter and surface roughness reduced runoff. Given the low coefficient of variation at all three levels, this residue behaves relatively uniformly.

Mean soil loss in this treatment is about 60% lower than in the control. A clear trend is observed in the straw waste treatment. Soil loss increases as biochar increases from 300 to 1500 g m⁻². This waste, with its light texture, strongly stabilizes surface particles, increases interparticle adhesion, and reduces erosion. The coefficient of variation indicates the reliability of the results. This treatment performed statistically better than the control. In the tissue waste treatment, the mean soil loss significantly decreased at the 900 g m⁻² level, indicating that at this slope, the mean amount of biochar has the most optimal effect on soil surface stabilization (Fig. 3). The low coefficient of variation at this level also indicates high stability and repeatability of the results. Tissue waste, due to its fibrous structure and tendency to absorb water, increases surface porosity and reduces initial runoff in the presence of porous biochar; however, at high amounts, it may cause surface swelling and loss of adhesion between particles. This treatment reduces loss by 60% compared to the control. Slope is usually one of the most important factors in intensifying water erosion and increasing soil loss (Shi et al., 2021; Sedaghatkish et al., 2025), but in this experiment, applying porous biochar with organic waste significantly reduced sediment and soil loss compared to the control treatment.

The contrasting responses among feedstocks indicate that biochar-specific properties, rather than biochar addition, governed the erosion response. Differences in particle size, pore architecture, ash content, surface chemistry, and water affinity can change how much biochar alters soil porosity and water redistribution. Thus, the absence of a strictly monotonic response at all application rates, particularly for sawdust- and vineyard-derived materials, should not be interpreted as experimental variability alone. Rather, it suggests an optimum amendment rate at which the beneficial hydraulic effects of biochar outweigh potential changes in pore connectivity or water movement.

Total soil loss (g) also shows a 15% slope across the study treatments (Table 1). Across all treatments, loss decreased with higher biochar levels (i.e., 900 and 1500 g m⁻²). The mean soil loss in the vineyard pruning treatment was slightly different from that of the control, and in some replicates, it was even higher than that of the control. This indicates that at a 15% slope, the effect of vineyard biochar on erosion control has been relatively reduced. The mean loss in the palm grove pruning treatment across all biochar levels, especially at 1500 g m⁻², was significantly lower than in the control (70 to 85%). This indicates that palm fiber charcoal effectively stabilizes sloping soils. In the sawdust treatment, mean total loss was approximately 40–55% lower than in the control, with a trend toward decreasing erosion as biochar levels increased. In the straw waste treatment, the mean soil loss was significantly lower than in the control. Straw biochar, with its high porosity and high moisture retention, enhanced the formation of stable soil particles and protected fine particles from separation by rain. A study by Al-Omran et al. (2021) reported that using biochar in soil resulted in more stable soil aggregates and a significant reduction in sheet erosion. The mean value for tissue waste treatment was lower than that of the control. This effect is due to the soft, cellulosic structure and high water-absorption capacity. Overall, all treatments improved significantly over the control, but differences between treatments varied with the waste's texture and the charcoal's porosity.

The total soil loss (g) values for the 27% slope in the study treatments showed that increasing the slope from 15 to 27% intensified sheet erosion (Table 1). However, biochar across all treatments significantly reduced soil loss, although the efficiency pattern differed from that on lower slopes. The mean soil loss during vineyard pruning waste treatment varied. At a charcoal level of 900 g m⁻², wastage decreased compared to the control, whereas at 300 g m⁻², it increased. For palm tree pruning waste, the mean waste at 1500 g m⁻² was significantly lower than in the control. Palm-pruning biochar, with a fibrous texture and high porosity, increased water absorption and reduced runoff. In the sawdust treatment waste, the mean was lower than in the control at all

levels, especially at 1500 g m^{-2} . The low standard deviation and low coefficient of variation indicate high uniformity and stability of the treatment. The mean loss in straw waste treatment decreased most at 1500 g m^{-2} . Due to its porous, lightweight structure, straw biochar has a high capacity to absorb water and form stable soil aggregates that prevent particle separation. In tissue waste treatment, the mean loss at 300 g m^{-2} exceeded that of the control. Because the biochar was incorporated throughout the soil layer, the higher sedimentation response observed for conventional tissue-derived biochar at lower application rates was not sufficient to produce measurable improvement of the soil-water system under the higher hydraulic force generated at the 27% slope. This result further indicates that biochar effectiveness is not solely a function of its presence in the soil, but depends on interactions among application rate, material properties, slope gradient, and rainfall-induced runoff energy. Porous biochar increases soil surface moisture by absorbing and retaining water within its pores, preventing soil particles from breaking apart. Increased cohesion between particles and improved soil particle stability make the soil more resistant to particle separation, even on steep slopes (Lehmann and Joseph, 2015). These findings are consistent with several studies. For example, Chen and Zhou (2022) reported that applying 10% biochar to sandy soils significantly reduced sediment discharge and increased the hydraulic stability of the soil surface.

In contrast, Rončák et al. (2023) showed that biochar, while reducing sediment load, improved soil structural stability and increased the water infiltration coefficient on sloping lands. Compared with the results for lower slopes (8% and 15%), the results show that although increasing the slope increases total sediment, the reducing effect of porous biochar is maintained at all levels; even at a slope of 27%, it remains effective. This indicates that biochar performs well under all conditions and can serve as an effective amendment to reduce surface soil erosion. In the treatment with a high level of porous biochar (1500 g m^{-2}), soil stability and uniformity under precipitation were greater than in other treatments.

Table 2 shows total soil sediment concentration values (g mL^{-1}) for the 8% slope across the study treatments, indicating that applying porous biochar across all waste treatments significantly reduced total soil sediment concentration compared to the control treatment. At a lower slope (8%), biochar's physical role is to increase permeability, improve particle adhesion, and reduce surface runoff.

The mean sediment concentration in the vineyard pruning waste treatment showed the greatest decrease compared to the control (900 g m^{-2}). A smaller decrease was also observed at 1500 and 300 g m^{-2} . The mean sediment concentration in the palm pruning waste treatment decreased significantly relative to the control at 1500 g m^{-2} . The 900 g m^{-2} level also had the lowest standard deviation and coefficient of variation, indicating greater uniformity in palm biochar yield under low-slope conditions. The mean sediment concentration in sawdust waste varies. Although the difference from the control at the 900 and 300 g m^{-2} levels is not large, at 1500 g m^{-2} there is a significant decrease relative to the control. In a study by Liu et al. (2021), biochar in light-textured soils increased water-holding capacity by 25% and reduced sediment concentration by 50%. The straw treatment showed variable means across different charcoal levels. At 900 g m^{-2} , sediment concentration decreased significantly relative to the control. Straw biochar, with its light structure and high specific surface area, is highly stable in water absorption and is particularly effective on low slopes. The mean sediment concentration in the paper towel treatment varied and was lower than in the control. The lowest concentration was observed at 900 g m^{-2} . Because of charcoal's cellulosic nature and high absorption capacity, it is highly effective at reducing sedimentation on low slopes. This phenomenon is consistent with Vahidi et al. (2025), who showed that biochar significantly improves soil structural stability by increasing effective soil porosity and reducing bulk density, thereby reducing the number of soil particles suspended in surface flow.

Total soil sediment concentration values (g mL^{-1}) for the 15% slope in the study treatments are shown (Table 2). Increasing the slope to 15% resulted in higher sediment concentrations across all treatments than at the 8% slope because surface flow and runoff energy are higher on the 15% slope. However, using porous biochar in all treatments significantly decreased sediment concentration compared with the control. The mean sediment concentration in the vineyard treatment at 1500 g m^{-2} was higher than at 900 g m^{-2} and lower than at 300 g m^{-2} , but all three treatments performed worse than the control. The mean sediment concentration in the palm-pruning waste treatment was significantly lower than in the control. The 900 g m^{-2} palm-pruning biochar surface showed a mean 35% reduction in sediment concentration compared to the control and a low coefficient of variation, indicating a uniform effect. In the sawdust waste treatment, the mean sediment concentration varied. At 900 g m^{-2} , the mean sediment concentration was higher than in the control, but at 1500 g m^{-2} , it was significantly lower. Overall, the effect of sawdust on sediment reduction was dependent on the level used. The straw treatment was among the most stable and effective for reducing sediment concentration. The means vary, showing a reduction of about 45–70% compared to the control. A low coefficient of variation indicates a stable effect.

Recent studies have also reported similar results. Lu (2024), in a review study, showed that applying biochar at optimal levels reduces erosion and sediment concentration, whereas excessive levels may have the opposite effect. Also, Zhao et al. (2013), in a simulated study, emphasized that uniform biochar distribution plays a key role in effective sediment control. The lowest mean sediment concentration in the tissue waste treatment was observed at 1500 g m^{-2} , about 15% lower than the control. However, the 300 g m^{-2} level was higher than the control. Table 2 shows the total soil sediment concentrations (g mL^{-1}) for a 27% slope across the study treatments. Increasing the slope from 15% to 27% increases runoff energy and the soil particle-carrying capacity. This is observed in the results: in most treatments, sediment concentration on this slope increased compared with lower slopes. However, applying porous biochar significantly prevented excessive sediment concentration.

The mean sediment concentration in the vineyard waste treatment at the 1500 g m^{-2} level is higher than in the control, whereas at the lower levels (900 and 300 g m^{-2}) it is about 35% lower. The mean sediment concentration in the palm pruning waste treatment is higher than in the control, and the coefficient of variation indicates unstable behavior of this treatment on a high slope. At 1500 g m^{-2} , the sediment concentration was lower than in the control, whereas at lower levels, it increased significantly. Sawdust residue treatment shows stable results. The mean sediment concentration across all levels was lower than that of the control. At the 1500 g m^{-2} level, sediment concentration was about 50% lower than in the control. The low coefficient of variation indicates that the sawdust biochar effect is uniform and stable. The mean sediment concentration of straw residue at 900 g m^{-2} shows a relatively large decrease

compared to the control. However, at 300 g m⁻², it is nearly equal to the control. In tissue paper waste treatment, the mean sediment concentration at 1500 g m⁻² was lower than in the control. As slope increased and surface area decreased, efficiency declined, and at 300 g m⁻², sediment concentration was even higher than in the control. These results are consistent with Liu et al. (2017) on semi-arid soils in Kenya, which showed that adding 5% biochar reduced sediment concentration by 40%. In a similar study, Sharma (2024) concluded that biochar in agricultural soils reduces the transport of dissolved organic matter and increases water permeability. The results indicate that using porous biochar at high levels, especially 1500 g m⁻², can effectively reduce sediment concentration and soil loss volume. Tables 4 and 5, and Figs. 4–6 present the comparison of soil loss and sediment concentration across the replicated treatments.

Table 4
Comparison of soil loss volume in study treatments using GLM and analysis of variance with and without tissue factory waste

	Study components	Degrees of freedom	Mean square	F-statistic	Significance level
With tissue factory waste	Level	2	54.210	4.775	0.001
	Slope	2	101.983	8.983	0.001
	Treatment	2	193.489	17.043	0.001
	Level × Slope	4	24.347	2.145	0.944
	Level × Treatment	4	20.362	1.794	0.094
	Slope × Treatment	4	25./533	2.249	0.433
	Level × Slope × Treatment	8	11.228	0.994	0.972
Without tissue factory waste	Level	2	12.092	2.862	0.062
	Slope	2	27.483	6.504	0.002
	Treatment	2	14.530	1.579	0.036
	Level × Slope	4	14.530	1.595	0.181
	Level × Treatment	4	6.262	1.482	0.213
	Slope × Treatment	4	26.678	6.313	0.001
	Level × Slope × Treatment	8	8.759	2.073	0.045
Without tissue factory waste	Slope	2	27.483	5.442	0.006
	Treatment	2	14.530	2.867	0.061
	Slope × Treatment	4	26.678	5.264	0.001

Table 5
Results of One-Way ANOVA analysis of variance to detect the unilateral effects of study treatments on soil loss, sediment concentration, and splash erosion at different slopes (i.e., 8, 15, and 27%)

Study components	Level used	change resources	Degrees of freedom	Mean square			F-statistic			Significance level		
				8	15	27	8	15	27	8	15	27
Soil loss	1500	Between Group	5	47.908	140.001	139.804	16.985	268.776	56.382	0.001	0.001	0.001
		Within Group	12	2.821	0.521	2.280						
		Total	17									
	900	Between Group	5	47.522	22.552	32.784	76.522	21.928	7.252	0.001	0.073	0.002
		Within Group	12	0.621	1.028	4.521						
		Total	17									
	300	Between Group	5	15.352	85.155	54.924	13.287	235.627	8.350	0.001	0.013	0.001
		Within Group	12	1.155	0.361	6.578						
		Total	17									
Sediment concentration	1500	Between Group	5	56.928	187.795	180.362	2.382	21.775	20.376	0.101	0.001	0.001
		Within Group	12	23.896	8.632	8.852						
		Total	17									
	900	Between Group	5	77.645	97.00	72.445	6.142	15.593	3.923	0.005	0.001	0.024
		Within Group	12	12.642	6.221	18.465						
		Total	17									
	300	Between Group	5	47.458	184.781	67.437	2.381	6.342	5.632	0.101	0.004	0.007
		Within Group	12	19.932	29.134	11.974						
		Total	17									
Splash erosion (Right gutter)	1500	Between Group	5	0.043	0.036	0.034	7.946	58.566	12.757	0.002	0.001	0.001
		Within Group	12	0.005	0.003	0.003						
		Total	17									
	900	Between Group	5	0.12	0.024	0.017	4.028	21.224	5.832	0.022	0.001	0.006
		Within Group	12	0.003	2.001	0.003						
		Total	17									
	300	Between Group	5	0.027	0.020	0.011	11.302	14.597	1.418	0.001	0.001	0.286
		Within Group	12	0.002	0.001	0.008						
		Total	17									
Splash erosion (Left gutter)	1500	Between Group	5	0.040	0.30	0.029	21.120	9.569	11.533	0.001	0.001	0.001
		Within Group	12	0.002	0.003	0.002						
		Total	17									

900	Between Group	5	0.011	0.015	0.019	3.111	8.553	7.123	0.50	0.001	0.003
	Within Group	12	0.004	0.002	0.003						
	Total	17									
300	Between Group	5	0.023	0.026	0.015	3.494	6.445	2.332	0.035	0.004	0.107
	Within Group	12	0.007	0.004	0.006						
	Total	17									

Table 4

Table 5

Figure 4

Figure 5

Figure 6

Table 4 shows the results of the generalized linear model and analysis of variance, which show that soil loss is significantly ($p < 0.05$) affected by the main factors of surface, slope, and treatment, indicating the multifactorial and complex nature of the soil erosion process. The significance of the biochar type and application rate factor indicates that soil surface characteristics, including cover type and surface roughness, play an important role in inhibiting particle detachment and transport. Studies show that surface changes can significantly affect soil loss rates by altering raindrop impact energy and by reducing or increasing the continuity of surface flow (Abrol et al., 2016). The significant effect ($p < 0.001$) of slope with an F statistic of (8.983) indicates that slope was the dominant factor in reducing soil loss (Fig. 4). Increasing slope increases sediment carrying capacity and intensifies the process of transporting detached particles. Recent studies have emphasized that soil loss is more sensitive to slope than runoff because even a limited increase in runoff on steep slopes can lead to a significant increase in erosion (Nearing et al., 2017). The significance ($p < 0.001$) of the treatment factor indicates that it effectively reduces erosion processes (Figs. 4–6). The treatments probably reduced soil loss by reducing the energy of rain impacts, increasing soil cohesion, increasing permeability, and disrupting the continuity of surface flow. Recent studies show that additive treatments usually have a stronger effect on soil loss than runoff, because even a limited reduction in flow energy can significantly reduce sediment transport (Wu et al., 2022).

In the interaction effects study, the non-significance ($p > 0.05$) of the surface $\times$ slope and surface $\times$ treatment interactions indicates that the effect of surface characteristics on soil loss depends on slope and surface conditions. This result is consistent with recent studies showing that the effects of soil cover and surface conditions are stronger on low- to moderate-slope soils than on high-slope soils. Recent studies have also emphasized that conservation-measure design should be tailored to soil surface conditions, because soil erosion responses to treatments can differ significantly across surfaces (Keesstra et al., 2019). In contrast, the non-significant ($p < 0.05$) slope $\times$ treatment interaction indicates that treatment effects on soil loss were relatively similar across slopes. This may indicate that the treatments applied were sufficiently intense and effective to partially inhibit the slope effect. Similar results suggest that some conservation measures, especially those that interrupt surface flow continuity, can perform relatively consistently across a range of slopes (Prosdocimi et al., 2016). The non-significance ($p > 0.05$) of the triple interaction of surface $\times$ slope $\times$ treatment indicates that the effect of treatments on erosion can be explained within a single-factor framework and that the absence of combined surface and slope conditions can change the direction of the treatment effect. The non-significance ($p > 0.05$) of the triple interaction of surface $\times$ slope $\times$ treatment indicates that although dual interactions play an important role in controlling soil loss, the simultaneous effect of these three factors in combination did not lead to a significant change ($p < 0.05$) (Figs. 4–6).

Table 4 shows the results of the generalized linear model and analysis of variance for soil loss without the paper towel treatment. The non-significance ($p > 0.05$) of the surface factor indicates that surface alone did not play a decisive role in changes in soil loss. Recent studies have also emphasized that soil loss is an indicator that does not necessarily change with increasing surface area or scale and may even show similar values across different surfaces (Nearing et al., 2017). In contrast, the significant ($p < 0.05$) slope factor indicates that increasing slope is associated with higher soil loss and sediment concentration. This reflects increased flow shear energy and sediment-carrying capacity on steeper slopes, so even if runoff volume is constant, soil loss and sediment concentration can increase. Studies have shown that soil loss and sediment concentration are highly sensitive to slope, and that as slope increases, the ratio of suspended sediment to runoff increases significantly (Deng et al., 2019). The significance ($p < 0.05$) of the treatment factor indicates that the treatment effectively reduced soil outflow loss without using tissue waste (Figs. 4–6). Recent studies emphasize that some conservation treatments may only reduce runoff volume to a limited extent. However, they play an important role in reducing soil loss and sediment concentration by reducing flow energy and increasing sedimentation. The significant ($p < 0.05$) slope $\times$ treatment interaction indicates that treatment effectiveness depended on slope conditions.

Figure 5 further shows the erosion severity map, showing that as slopes steepen from 15 to 27%, runoff soil-loss capacity increases exponentially. However, the data reveal a critical threshold at an application rate of 155 g m^{-2} , which effectively neutralizes the slope penalty. It also shows that high application rates provide sufficient surface friction and aggregate stability to maintain protection even when runoff shear force is maximized on steeper slopes.

Overall, the results support a coupled hydrological–erosional mechanism for mitigating sheet erosion through biochar incorporation. The results suggest that biochar characteristics and application rate modified the soil–water environment, influencing infiltration, temporary water storage, runoff generation, and the

subsequent detachment and transport of fine loess particles. The stronger response of some engineered porous biochar than conventional tissue-paper-derived biochar further suggests that pore structure and material-specific properties may be key determinants of erosion-control performance. Nevertheless, because this experiment did not independently measure hydraulic conductivity, infiltration rate, surface sealing, or direct raindrop energy dissipation, these processes should be regarded as plausible mechanisms rather than experimentally isolated causal pathways. Future experiments integrating rainfall simulation with direct measurements of infiltration, hydraulic conductivity, soil surface sealing, wettability, and sediment detachment would help quantitatively separate these mechanisms.

Effect of Porous Biochar on Splash Erosion

To evaluate splash erosion in the study and control treatments, we measured right- and left-splash using splash gutters. The results and statistical criteria of the splash erosion in the study treatments at three rates of 1, 3, and 5% by weight (i.e., 300, 900, and 1500 g m⁻²) by weight and three slopes of eight, 15, and 27 percent are presented in Table 3, the results of the statistical comparison, and optimization curve neutralizing the slope penalty at different application rates are presented in Table 4 and Figs. 5–8.

Table 3

Total splash values (g) from experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from

Raw material	Plot number and descriptive statistics	Control			300						900					
		8		15		27		8		15		27		8		15
		R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
Vineyard pruning	1	0.42	0.45	0.44	0.42	0.56	0.55	0.16	0.41	0.49	0.45	0.53	0.37	0.24	0.29	0.3
	2	0.43	0.44	0.46	0.48	0.44	0.48	0.27	0.11	0.48	0.47	0.47	0.32	0.38	0.42	0.3
	3	0.44	0.44	0.40	0.47	0.53	0.56	0.12	0.14	0.48	0.65	0.38	0.34	0.36	0.38	0.4
	Mean	0.42	0.44	0.43	0.46	0.51	0.53	0.18	0.22	0.48	0.52	0.46	0.34	0.33	0.36	0.3
	Standard Deviation	0.01	0.01	0.03	0.03	0.06	0.04	0.08	0.17	0.00	0.11	0.08	0.03	0.08	0.07	0.0
	Coefficient of Variation (%)	1.79	1.97	7.19	6.47	12.22	7.90	42.75	75.56	0.88	21.29	17.23	8.47	24.23	18.02	10.
Palm pruning	1	0.37	0.32	0.43	0.41	0.38	0.47	0.30	0.27	0.40	0.46	0.52	0.54	0.26	0.28	0.3
	2	0.36	0.30	0.35	0.38	0.34	0.48	0.30	0.31	0.35	0.35	0.49	0.40	0.23	0.29	0.3
	3	0.42	0.43	0.32	0.37	0.40	0.50	0.36	0.47	0.30	0.31	0.25	0.30	0.23	0.23	0.3
	Mean	0.38	0.35	0.37	0.39	0.37	0.48	0.32	0.35	0.35	0.37	0.42	0.41	0.24	0.27	0.3
	Standard Deviation	0.03	0.07	0.06	0.02	0.03	0.01	0.03	0.11	0.05	0.08	0.15	0.12	0.02	0.03	0.0
	Coefficient of Variation (%)	8.75	20.56	15.51	5.38	8.42	2.87	10.90	30.70	14.29	20.81	35.62	29.12	7.26	12.71	7.7
Sawdust	1	0.26	0.29	0.31	0.33	0.45	0.42	0.30	0.27	0.35	0.32	0.42	0.41	0.43	0.39	0.2
	2	0.28	0.36	0.32	0.35	0.58	0.53	0.22	0.30	0.34	0.31	0.37	0.30	0.33	0.27	0.2
	3	0.26	0.27	0.33	0.32	0.57	0.51	0.28	0.26	0.31	0.34	0.39	0.33	0.36	0.39	0.3
	Mean	0.27	0.31	0.32	0.33	0.53	0.48	0.27	0.27	0.36	0.32	0.39	0.35	0.37	0.35	0.2
	Standard Deviation	0.01	0.05	0.01	0.01	0.07	0.06	0.04	0.02	0.02	0.02	0.03	0.06	0.05	0.07	0.0
	Coefficient of Variation (%)	4.92	15.37	3.74	3.98	13.15	12.29	15.56	7.18	6.50	4.82	7.58	17.01	13.40	20.05	7.2
Rice straw	1	0.44	0.48	0.47	0.43	0.65	0.68	0.13	0.15	0.22	0.23	0.46	0.48	0.33	0.29	0.2
	2	0.41	0.42	0.44	0.39	0.46	0.26	0.13	0.10	0.23	0.22	0.40	0.41	0.16	0.16	0.2
	3	0.46	0.49	0.50	0.45	0.41	0.39	0.15	0.12	0.32	0.34	0.43	0.48	0.21	0.28	0.2
	Mean	0.44	0.46	0.47	0.42	0.51	0.44	0.13	0.12	0.25	0.26	0.43	0.46	0.23	0.24	0.2
	Standard Deviation	0.03	0.04	0.03	0.03	0.13	0.22	0.01	0.02	0.05	0.07	0.03	0.04	0.09	0.07	0.0
	Coefficient of Variation (%)	6.13	8.37	6.07	6.33	25.73	25.39	9.15	19.75	21.39	25.45	7.28	8.25	28.41	30.09	7.3
Tissue factory	1	0.36	0.37	0.52	0.48	0.51	0.52	0.34	0.23	0.29	0.37	0.33	0.42	0.28	0.25	0.3
	2	0.43	0.35	0.44	0.39	0.39	0.43	0.25	0.23	0.31	0.36	0.37	0.46	0.32	0.24	0.3
	3	0.42	0.34	0.49	0.45	0.49	0.53	0.22	0.20	0.35	0.39	0.28	0.48	0.34	0.20	0.4
	Mean	0.40	0.35	0.48	0.44	0.46	0.49	0.27	0.22	0.32	0.37	0.33	0.45	0.32	0.23	0.3
	Standard Deviation	0.04	0.01	0.04	0.05	0.07	0.05	0.06	0.02	0.03	0.02	0.05	0.03	0.03	0.03	0.0
	Coefficient of	9.40	3.87	8.15	10.46	14.21	11.09	22.35	6.88	9.52	4.31	14.08	7.40	9.90	12.01	12.

Table 3

Table 4

Figure 7

Figure 8

Table 3 shows the results of the splatter simulation on an 8% slope, influenced by waste type, porous carbon amount, and splatter chute position (right or left). In general, the splatter values in treatments with porous carbon were lower than in the control, and this decrease was more pronounced with increasing carbon content, indicating its effective role in reducing the separation and splatter of soil particles from raindrop impact (Blanco-Canqui, 2017). Table 5 presents the statistical results, showing that all three levels across the three slopes significantly reduced splash.

Except for the 300 g m^{-2} level on the 27% slope, the results are not significant. Vineyard waste porous carbon treatments at 1500, 900, and 300 g m^{-2} on an 8% slope significantly reduced splash volume compared to the control (Figs. 7–8). The 300 g m^{-2} treatment reduced splash more effectively than the 900 g m^{-2} treatment. Increasing the level to 1500 g m^{-2} also reduced splashes. The results show that at this treatment level, the high porous carbon content reduced splash, and the porous structure controlled it effectively. On the other hand, the porous carbon treatment for palm pruning resulted in a splash amount of 0.13 and 0.18 g at the level of 1500 g m^{-2} of the right and left gutters, respectively, which was about twice as much as the other two levels, significantly reducing splash erosion (Figs. 7–8). So, the treatment with a level of 900 g m^{-2} in the right and left gutters was 0.24 and 0.27 g, respectively, and in the porous carbon treatment with a level of 300 g m^{-2} of the palm grove pruning, the amount of splash in the right and left gutters was 0.35 and 0.32 g, respectively. The increasing trend in porous carbon indicates that raindrop impact energy has decreased and, with improved soil surface aggregates, particle splashing has decreased (Blanco-Canqui, 2017; Khademalrasoul et al., 2019). In the porous carbon treatment of sawdust, the lowest amount of splashing is associated with a surface area of 1500 g m^{-2} . So, the average weight in the right and left gutters was reported as 0.16 and 0.15 g, respectively (Figs. 7–8). Reducing the carbon level to 900 and 300 g m^{-2} increased splashing, reaching about 0.35–0.37 g at 900 g m^{-2} and 0.27 g at 300 g m^{-2} . This trend indicates that increasing carbon porosity dissipates raindrop impact energy and prevents particle splashing by improving soil particle stability (Khademalrasoul et al., 2019).

In the porous carbon of straw, the effect of porous carbon is observed more clearly. At the level of 1500 g m^{-2} , the average scattering is very low and is about 0.10 to 0.12 g, which indicates the highest efficiency of this compound in suppressing scattering. At 900 g m^{-2} , scattering increases to about 0.23–0.24 g. At the level of 300 g m^{-2} , the scattering also increases, and its mean reaches about 0.13 to 0.12 g. In the tissue carbon treatment, the amount of splash is higher and more unstable than in the porous vineyard carbon treatment compared to the other three porous carbons. Although using 1500 g m^{-2} carbon caused a relative decrease in splash, the averages remained between 0.20 and 0.30 g. At 900 and 300 g m^{-2} levels, splash increased. These results indicate that the tissue carbon structure has a lower capacity compared to sawdust and straw. In the control treatment, splash was highest at all levels, with mean splash in the right and left splash gutters ranging from 0.42 to 0.44 g. These high values indicate the extreme vulnerability of the soil surface without amendment to raindrop impact. In general, the treatment comparison shows that applying porous carbon, especially at 1500 g m^{-2} and in combination with porous carbon from straw or sawdust, is the most effective solution for reducing splash on an 8% slope and can play an important role in controlling primary water erosion.

Table 3 shows changes in soil splashing on a 15% slope, affected by the type and amount of porous carbon and the location of the splashing gutters, and clearly indicates that increasing the slope beyond 8% generally increased splashing intensity. However, treatment effects still depend on the amount of carbon and the type of waste, and treatments with additives perform better than the control (Blanco-Canqui, 2017). The results from the vineyard waste porous carbon treatment show that, at a treatment level of 900 g m^{-2} , the average splash in the right and left gutters is 0.36 and 0.39 grams, respectively. This is lower than the other two levels and has improved and stabilized soil particles on the soil surface. Splash increased in the other two treatments at 1500 and 300 g m^{-2} , respectively. The porous carbon treatment of the palm pruning at the level of 1500 g m^{-2} has a lower mean splash than the other two levels. The mean amounts in the right and left splash gutters are 0.21 and 0.23 g, respectively, indicating the effectiveness of this treatment in reducing and controlling splash (Figs. 7–8). At 900 and 300 g m^{-2} , average splash in the right and left splash gutters was about 0.32 and 0.33 g, respectively, and 0.35 to 0.37 g.

In the sawdust porous carbon treatment, the lowest splash values were at the 1500 g m^{-2} level, and the average splash values in the right and left splash chutes were about 0.19 and 0.18 g, respectively. At the 900 g m^{-2} level, splash increased, with an average of about 0.28 to 0.26 g. At the 300 g m^{-2} level, splash increased, with an average value of about 0.34 g. This increasing trend indicates that as the amount of porous carbon decreases, the soil surface's ability to absorb raindrop impact energy decreases, and particle separation increases. In straw-clay porous carbon, the amount of splash is more uniform than in sawdust-based porous carbon, and fewer changes are observed with the change in the amount of porous carbon. The mean splash at 1500 g m^{-2} is about 0.25 to 0.26 g, and as carbon decreases to 900 and 300 g m^{-2} , this value increases only slightly, reaching about 0.23 to 0.26 g. Lower coefficients of variation than other wastes indicate that combining straw and porous carbon created a more stable soil surface and absorbed raindrop impact to an acceptable extent, even on a 15% slope (Blanco-Canqui, 2017). In the tissue carbon treatment, splash values are relatively high with less fluctuation. At the 1500 g m^{-2} carbon level, the average splash in the right and left splash chutes is about 0.29 and 0.34 g, respectively. At the 900 g m^{-2} level, these values increase to about 0.36 and 0.38 g, and at the 300 g m^{-2} level, the splash is 0.32 and 0.37. The control treatment had the highest amount of splashing at all

levels. The mean splashing in the right and left splashing gutters was reported to be about 0.47 to 0.42 g, which is much higher than all treatments. These high values indicate the extreme sensitivity of soil without additives to increases in slope and raindrop-impact intensity.

Table 3 shows that soil spalling occurs at a 27% slope, creating more critical erosion conditions than at 8% and 15%. In general, increasing the slope intensified raindrop impact energy and increased soil-particle separation, resulting in greater splash in all treatments than at lower slopes (Blanco-Canqui, 2017). The vineyard porous carbon treatment had the lowest splash amounts at the 1500 g m⁻² level, with average splash amounts in the right and left splash chutes of about 0.34 and 0.41 g, respectively. At the 900 and 300 g m⁻² levels, the splash amount increased to averages of 0.47 and 0.48 g, respectively. The average amount of splash increased at the 300 g level, and its values were reported as 0.34 and 0.46 g, respectively. At a slope of 27%, the average splash increased in the pore carbon treatment of the palm grove. At 1500, 900, and 300 g m⁻², the average splash in the right gutter was 0.31, 0.36, and 0.42 g, respectively, and in the left gutter was 0.32, 0.38, and 0.41 g, respectively.

In the sawdust porous carbon treatment, splashing is lowest at 1500 g, with averages of about 0.23 and 0.21 g in the right and left splashing gutters, respectively. At the level of 900 g m⁻², splashing increases, and its average reaches about 0.32 to 0.29 g. At 300 g m⁻², splashing is highest in this porous carbon, averaging about 0.35–0.39 g. This trend indicates that on steep slopes, porous carbon plays a much more pronounced role in weakening the impact effect of rain and increasing soil-surface stability. In the porous carbon of straw, the amount of splash is slightly higher and more uniform than that of sawdust. At the level of 1500 g m⁻², the mean splash is about 0.27 to 0.28 g, which is slightly higher than that of sawdust at the same level. At 900 g m⁻², splash increases to about 0.33–0.37 g, and at 300 g m⁻², it increases significantly to about 0.43–0.46 g. These results indicate that although straw provides a suitable cover for the soil surface, on steep slopes, the reduced amount of porous carbon can decrease its efficiency in controlling splash.

The greatest fluctuation in splash amount is observed in the paper-paper carbon treatment. At the 1500 g m⁻² level, the average splash in the right and left splash gutters is about 0.31 and 0.39 g, respectively, indicating a difference between the two sides of the plot. This pattern continues at the 900 and 300 g m⁻² levels, and, in some cases, the average splash exceeds 0.47 g. The high coefficients of variation in this treatment indicate that the paper-paper carbon behaves more unstably at the 27% slope and does not fully level the soil surface or reduce rain impact. The control treatment had the highest splash levels at all carbon levels. Mean splash across plots ranged from 0.46 to 0.49 g, much higher than in all treatments. This indicates that, without carbon, soil on a 27% slope is highly vulnerable to splash and the onset of erosion.

In general, as the application rate of porous biochar increased from 300 to 900 and then 1500 g m⁻², soil spalling decreased. However, the magnitude of this decrease depended on feedstock type and land slope. This suggests that increasing porous biochar content improves the soil's ability to resist particle detachment. Several studies also report that feedstock type is the most important factor determining biochar's specific surface area, pore volume, cation exchange capacity, and hydrological behavior. Ahmad et al. (2014) showed that changing the starting material can significantly affect biochar's physical properties and, consequently, its performance in soil conservation. Blanco-Canqui (2017) also showed that applying biochar can increase the stability of soil aggregates, reduce the effective energy of raindrops, and consequently limit the erosion and splashing of soil particles.

On the other hand, Jeffery et al. (2015) and Alkharabsheh et al. (2021) also stated that increased porosity and water-holding capacity from biochar addition improve soil structure and reduce sheet Erosion. Slope effects were also observed in all treatments. In general, increasing the slope from 8 to 27% increased the soil's susceptibility to particle detachment; however, porous biochars at higher rates partially neutralized this negative effect and reduced erosion. This indicates that biochar's protective role is maintained even when runoff shear force increases. The results of this section are consistent with the findings of Blanco-Canqui (2017), who reported that the protective effect of biochar is maintained even at high slopes. However, its intensity depends on the soil type, application rate, and biochar properties. Overall, Table 3 shows that increasing the application rate of porous biochar, regardless of feedstock, reduced the mass of particles separated from the soil, and this effect was more pronounced at rates of 900 and 1500 g m⁻². Feedstock origin also played an important role in biochar effectiveness, likely because the resulting biochars differed in physical and chemical properties.

Key Limitations and Constraints of the Study

Based on the study's findings, the following five concise paragraphs summarize its key limitations and constraints.

1. Scale and Generalizability Constraints

The experiments were carried out on small laboratory plots (0.5 × 0.5 m), and the results may not extrapolate to field-scale conditions. The hydrological processes occurring in small plots are very different from those occurring in natural watershed systems due to the "edge effects" and "boundary conditions" of the smaller plots, as well as scale-dependent hydrological processes occurring in small plots. In addition, the study used only loess soil from a specific area in Golestan Province, and the results may not apply to other soil types with different physicochemical properties, such as clayey, sandy, and organic soils.

2. Temporal and Environmental Limitations

All experiments were conducted in a controlled laboratory environment using a rain simulator, without reproducing natural rainfall variability, wind effects, temperature changes, or other field environmental factors. Each simulation took only 30 minutes, providing a short-term snapshot of the immediate erosion response. Thus, the longevity of biochar, its aging effects, cumulative changes in soil physical and chemical properties, and its effects under different rainfall intensities and patterns remain unstudied.

3. Biochar-Specific Limitations

The study tested only five feedstock types and produced biochar under specific pyrolysis conditions (initial temperature of 400°C and KOH activation at 800°C). The pH-activation following biochar production resulted in alkalinity that the study did not account for in soil chemistry and erosion processes; this alkalinity may have been caused by the biochar used. The study also tested only one activator (KOH) and did not systematically investigate the influence of biochar particle size. The fate of engineered biochar in varying production conditions and application practices is unknown.

4. Gaps in Process & Mechanism

Sheet and splash erosion were measured, but rill and gully erosion processes, which can contribute significantly to total soil loss, were not evaluated. The study did not measure the mechanisms underlying the reduction in erosion, except for changes in key soil physical properties (e.g., aggregate stability, hydraulic conductivity, bulk density). Furthermore, no studies examine the long-term effects of biochar aging, degradation, or leaching on erosion control, reducing mechanistic understanding.

5. Methodological and Validation Constraints

The study may have limited natural variability because it included only three replications per treatment, and some treatments had high coefficients of variation, resulting in high data scatter. The results have limited applicability because they were not tested in the field, and the study does not discuss the economic feasibility, cost-benefit analysis, or environmental risks of large-scale biochar application. Additionally, the results apply only to the rainfall intensity (70 mm h⁻¹) and slope classes (i.e., 8%, 15%, 27%).

Practical and Managerial Implications of the Study

The study, hinging on the effect of engineered porous biochar on sheet and splash erosion across different slopes, has strong practical and managerial implications. The results showed that the porous biochar produced can significantly reduce splash erosion, sediment concentration, and sheet erosion under all the slope gradients studied, particularly at a rate of 1500 g m⁻². Consequently, KOH-activated porous biochar is an effective and sustainable soil amendment for eroded loess soil areas. Producing engineered biochar from agricultural and industrial waste not only supports the sustainable valorization of these wastes but also enhances soil erosion protection.

This research clearly demonstrates that engineered porous biochar is a viable, sustainable approach for reducing sheet and splash erosion in loess soils. It can work on a variety of slopes and with different feedstocks, offering flexible solutions for different land-use conditions. Biochar application can be a significant step towards sustainable land management, reducing sediment transport and enhancing soil resilience when integrated into soil management practices, agricultural policies, and watershed management plans. The synergy of biochar application in waste valorization and erosion control makes it an attractive solution for advancing environmental and economic sustainability goals.

Conclusion Remarks

The results showed that applying porous biochars produced from various agricultural and industrial wastes effectively reduces sheet Erosion and soil spalling under simulated rainfall conditions. Regardless of feedstock type, increasing the biochar application rate reduced the mass of particles detached from the soil surface, indicating improved soil resistance to raindrop kinetic energy. This suggests that porous biochar, in addition to modifying soil physical properties, can effectively control the early stages of water erosion. The results also showed that feedstock source plays an important role in biochar performance. The observed differences among biochars derived from vineyard pruning, palm pruning, sawdust, rice straw, and tissue factory waste can be attributed to variations in structural features formed during pyrolysis and in their activity. A key aspect of this research was using porous bioproducted material prepared in two pyrolysis steps (initial production at 400°C and activation at 800°C). This process increased the biochar's porosity and specific surface area and likely helped enhance its erosion-control efficiency. This shows that, beyond raw material choice, biochar production conditions also determine its performance in soil conservation. From a practical perspective, the conversion of agricultural and industrial wastes into activated porous biochar can simultaneously pursue two important goals: first, sustainable management and valorization of organic wastes and reducing the environmental burden resulting from their disposal, and second, increasing soil resistance to erosion and helping to protect soil resources, especially in sloping lands and areas prone to heavy rainfall. Based on the results, porous biochar can be incorporated into soil conservation management strategies in semi-arid and arid regions as a sustainable soil amendment. However, to generalize the results of this research to field conditions, it is necessary to conduct long-term studies under natural conditions, investigate the behavior of different soil types and different rainfall intensities, and evaluate the simultaneous effects on runoff, water infiltration, soil aggregate stability, soil organic carbon, and soil biological activities.

Declarations

Author Contribution

1: Conceptualization, Methodology, Investigation, Validation, Resources, Writing and Editing, Supervision, Project administration2: Conceptualization, Methodology, Writing original draft preparation, Investigation.3: Conceptualization, Methodology, Writing original draft preparation, Investigation.4: Collection Data, Writing original draft preparation.5: Methodology, Reviewing and Editing6: Writing-Review & Editing, Supervision, Project administration7: Collection Data, Writing original draft preparation.8: Reviewing and Editing 9: Reviewing and Editing10: Reviewing and Editing11: Reviewing and Editing

Acknowledgement

This work was financially supported by the Iran National Science Foundation (INSF) under INSF-NSFC Joint Research Project (No. 4021328). It was also jointly financed by the National Natural Science Foundation of China (No. 42361144707). The Iran National Science Foundation (INSF), under project No. 4039768, has partially supported the research presented here.

Data Availability

Data Availability: The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

References

1. AbdelRahman, M. A. An overview of land degradation, desertification, and sustainable land management using GIS and remote sensing applications. *Rend. Lincei Scienze Fis. e Naturali*. **34** (3), 767–808 (2023).
2. Abel, S. et al. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma* **202**, 183–191 (2013).
3. Abrol, V. et al. Biochar effects on soil water infiltration and erosion under seal formation conditions: rainfall simulation experiment. *J. Soils Sediments*. **16** (12), 2709–2719 (2016).
4. Ahmad, M. et al. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* **99**, 19–33 (2014).
5. Alfei, S. & Pandoli, O. G. Bamboo-based biochar: A still too little-studied black gold and its current applications. *J. Xenobiotics*. **14** (1), 416–451 (2024).
6. Alkharabsheh, H. M. et al. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy* **11** (5), 993 (2021).
7. Al-Omran, A., Ibrahim, A. & Alharbi, A. Effects of biochar and compost on soil physical quality indices. *Commun. Soil Sci. Plant Anal.* **52** (20), 2482–2499 (2021).
8. Blanco-Canqui, H. Biochar and soil physical properties. *Soil Sci. Soc. Am. J.* **81** (4), 687–711 (2017).
9. Chen, X. & Zhou, B. Synergistic effects of nano-biochar and crop on reducing rainwater runoff and phosphorus loss from sloping farmland. *Arab. J. Geosci.* **15** (1), 43 (2022).
10. Christiansen, J. E. Irrigation by sprinkling. Berkeley: The University of California Agricultural Experiment Station. *Bulletin* (670): 124. (1942).
11. Deng, L. et al. Effects of rainfall intensity and slope gradient on runoff and sediment yield from hillslopes with weathered granite. *Environ. Sci. Pollut. Res.* **26** (31), 32559–32573 (2019).
12. Gharemahmudli, S. et al. A., (2023). Changes in overall and inter-variability of runoff and soil.
13. Loss for a loess soil resulted from a freezing–thawing cycle. *Environ. Monit. Assess.*, **195**:860. Doi.org/10.1007/s10661-023-11446-9
14. Govers, G. et al. A long flume study of the dynamic factors affecting the resistance of a loamy soil to concentrated flow erosion. *Earth. Surf. Proc. Land.* **15** (4), 313–328 (1990).
15. Islam, M. U., Jiang, F., Guo, Z. & Peng, X. Does biochar application improve soil aggregation? A meta-analysis. *Soil Tillage. Res.* **209**, 104926 (2021).
16. Jeffery, S., Verheijen, F. G., van der Velde, M. & Bastos, A. C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* **144** (1), 175–187 (2011).
17. Keesstra, S. D. et al. Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. *Catena* **174**, 95–103 (2019).
18. Khademalrasoul, A. et al. Short-term effects of biochar application on soil loss during a rainfall-runoff simulation. *Soil Sci.* **184** (1), 17–24 (2019).
19. Kumar, S., Gupta, R. & Lee, J. Thermal and chemical activation methods for the production of high-performance biochar. *Renew. Sustain. Energy Rev.* **160**, 112349 (2025).
20. Lee, C. H. et al. In-situ biochar application conserves nutrients while simultaneously mitigating runoff and erosion of a Fe-oxide-enriched tropical soil. *Sci. Total Environ.* **619–620**, 665–671 (2018).
21. Lee, S. S., Shah, H. S., Awad, Y. M., Kumar, S. & Ok, Y. S. Synergy effects of biochar and polyacrylamide on plants growth and soil erosion control. *Environ. Earth Sci.* **74** (3), 2463–2473 (2015).
22. Lehmann, J. & Joseph, S. (eds) *Biochar for environmental management: science, technology and implementation* 883 (Taylor & Francis, 2024).
23. Li, Y., Yang, J., Yang, M., Wang, B. & Zhang, F. Biochar application reduces soil detachment capacity by overland flow under a continuous three-year field experiment on the Loess Plateau of China. *Int. Soil. Water Conserv. Res.* **13** (3), 687–701 (2025).
24. Liu, Z., Dugan, B. & Masiello, C. A. Biochar stability and effects on soil erosion and hydrology. *Soil. Tillage Res.* **205**, 104769 (2021).
25. Liu, Z., Dugan, B., Masiello, C. A. & Gonnermann, H. M. Biochar particle size, shape, and porosity act together to influence soil water properties. *Plos one*, **12**(6), e0179079. (2017).
26. Lu, Y. Does biochar mitigate rainfall-induced soil erosion? A meta-analysis. *Geoderma* **438**, 116398 (2024).
27. Luo, S. et al. Long-term biochar application influences soil microbial community and its potential roles in semi-arid farmland. *Appl. Soil. Ecol.* **117**, 10–15 (2017).
28. Mumzaei, A., Sadeghi, S. H. R., Homaei, M. & Zarei Darki, B. Laboratory insights into the effects of gasoil contamination on runoff and soil loss behaviors. *Soil Tillage. Res.* **262**, 107225 (2026).

29. Nan, X. et al. Effects and mechanisms of zero-valent iron-loaded corn straw biochars on Cd (II) adsorption onto loessial soil. *Colloids Surf., A*. **737**, 139729 (2026).
30. Nearing, M. A., Xie, Y., Liu, B. & Ye, Y. Natural and anthropogenic rates of soil erosion. *Int. Soil. Water Conserv. Res.* **5** (2), 77–84 (2017).
31. Obia, A., Cornelissen, G., Martinsen, V., Smebye, A. B. & Mulder, J. Conservation tillage and biochar improve soil water content and moderate soil temperature in a tropical Acrisol. *Soil Tillage. Res.* **197**, 104521 (2020).
32. Ok, Y. S., Palansooriya, K. N., Yuan, X. & Rinklebe, J. Special issue on biochar technologies, production, and environmental applications in Critical Reviews in Environmental Science & Technology during 2017–2021. *Crit. Rev. Environ. Sci. Technol.* **52** (19), 3375–3383 (2022).
33. Pansak, W. et al. Spatial variations in runoff, sediment, and nutrient losses induced by toposequence and biochar application in upland maize farming. *Int. Soil. Water Conserv. Res.* **14** (1), 100551 (2026).
34. Prosdociimi, M., Tarolli, P. & Cerdà, A. Mulching practices for reducing soil water erosion: A review. *Earth Sci. Rev.* **161**, 191–203 (2016).
35. Rončák, P. et al. Effects of the application of biochar on the soil erosion of plots of sloping agricultural land with silt loam soil. *J. Hydrology Hydromechanics.* **71** (4), 356–368 (2023).
36. Sadeghi, S. H. R. & Parvizi, Y. *Study and Measurement of Water Erosion* 420 (Tarbiat Modares University, 2022).
37. Sadeghi, S. H. R., Ashgevar Heydari, M. & Jafarpour, A. Inhibability of soil loss and sediment concentration during consecutive rainfalls from experimental plots treated by endemic microorganisms. *Int. J. Sedim. Res.* **38**, 446–454 (2023).
38. Sadeghi, S. H. R. et al. Halting Erosion in Saline Soils Using a Novel Engineered Waste-Derived Porous Carbon Amendment. *International Soil. Water Conserv. Research*, 100677. (2026a).
39. Sadeghi, S. H. R. et al. The hydrologic behavior of loess and Marl soils in response to biochar and polyacrylamide mulching under laboratorial rainfall simulation conditions. *Journal Hydrology*, 125620. (2020a).
40. Sadeghi, S. H. R. et al. Field measurement of effects of individual and combined application of biochar and polyacrylamide on erosion variables in loess and marl soils. *Sci. Total Environ.* **728**, 138866 (2020b).
41. Sadeghi, S. H. R. et al. Reduction in soil loss caused by a freeze-thaw cycle through inoculation of endemic soil microorganisms. *Appl. Soil. Ecol.* **157**, 103770 (2021).
42. Sadeghi, S. H. R. et al. Introducing priority morph-genetic porous carbon for potential applications in soil and water conservation through Game Theory. *Biochar* **8**, 35 (2026b).
43. Saffari, N., Hajabbasi, M. A., Shirani, H., Mosaddeghi, M. R. & Owens, G. Influence of corn residue biochar on water retention and penetration resistance in a calcareous sandy loam soil. *Geoderma* **383**, 114734 (2021).
44. Sedaghatkish, F., Kapourchal, S. A. & Parhizkar, M. Efficiency of four types of biochar to improve soil properties and decrease soil detachment in vulnerable hillslopes to rill erosion. *Int. J. Sedim. Res.* **40** (3), 489–499 (2025).
45. Shapiro, S. S. & Wilk, M. B. An analysis of variance test for normality (complete samples). *Biometrika* **52** (3/4), 591–611 (1965).
46. Sharma, P. Biochar application for sustainable soil erosion control: a review of current research and future perspectives. *Front. Environ. Sci.* **12**, 1373287 (2024).
47. Shi, G., Wu, Y., Li, T., Fu, Q. & Wei, Y. Mid-and long-term effects of biochar on soil improvement and soil erosion control of sloping farmland in a black soil region, China. *J. Environ. Manage.* **320**, 115902 (2022).
48. Singh, A. et al. Addressing abiotic stresses and advancing SDGs by Biochar for sustainable agriculture and environmental restoration. *Egypt. J. Soil Sci.* **65** (1), 463–489 (2025).
49. Tucker, G. E. & Slingerland, R. Drainage basin responses to climate change. *Water Resour. Res.* **33** (8), 2031–2047 (1997).
50. Vahidi, M., Bayat, H. & Ebrahimi, M. Evaluating the impact of organic amendments on soil erosion dynamics: a comprehensive examination of application methods and timing. *Can. J. Soil Sci.* **105**, 1–14 (2025).
51. Verheijen, F. G. et al. The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma*, 347, 194–202.t (2019).
52. Wang, J. et al. Soil aggregate stability and its response to overland flow in successive Eucalyptus plantations in subtropical China. *Sci. Total Environ.* **807**, 151000 (2022).
53. Wu, L., Liu, X., Yu, Y. & Ma, X. Biochar, grass, and cross-ridge reshaped the surface runoff nitrogen under consecutive rainstorms in loessial sloping lands. *Agric. Water Manage.* **261**, 107354 (2022).
54. Xu, W., Whitman, W. B., Gundale, M. J., Chien, C. C. & Chiu, C. Y. Functional response of the soil microbial community to biochar applications. *Gcb Bioenergy.* **13** (1), 269–281 (2021).
55. Yu, P. et al. Effect of biochar on soil and water loss on sloping farmland in the black soil region of Northeast China during the spring thawing period. *Sustainability* **13** (3), 1460 (2021).
56. Zhang, D., Sun, B. H., Fan, T. & Y Preparation and microstructure analysis of biomimetic materials. *Sci. China Ser. E Eng. Mater. Sci.* **34** (7), 721–729 (2004).
57. Zhang, Q. R., Ji, L. Y., Gao, C. C., Lü, H. H. & Yong, S. O. Preparation of modified biochar and its application in environmental remediation. *J. Agro-Environment Sci.* **40** (5), 913–925 (2021).
58. Zhang, Q. et al. Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. *J. Clean. Prod.* **242**, 118435 (2020).

Figures



Fig. 1 Steps in the production of genetically modified porous carbon in a thermal furnace: Mixing the initial biochar with activator and water (a, b), placing it inside the furnace (c), porous carbon from tissue paper waste (d), straw (e), grinding and sieving the product (f), final product (g)

Figure 1

See image above for figure legend.

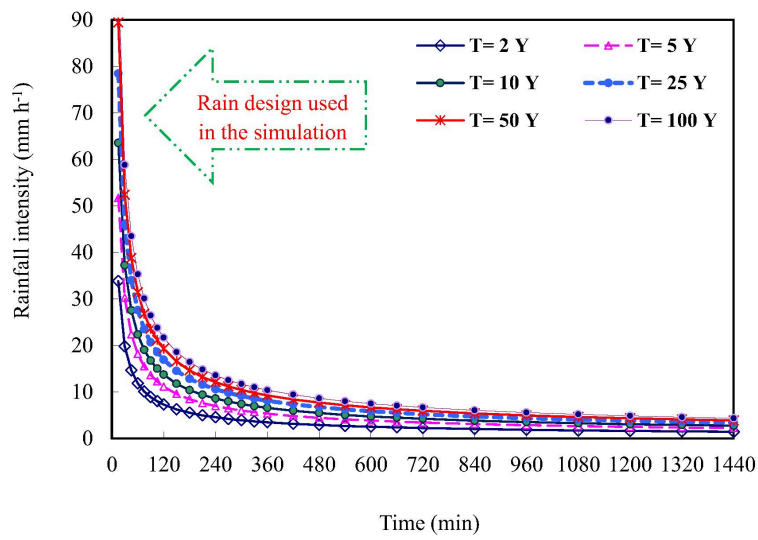


Fig. 2 Precipitation intensity-duration-abundance diagram of the Golidaghi-Maraveh Tepeh meteorological station in Golestan province

Figure 2

See image above for figure legend.

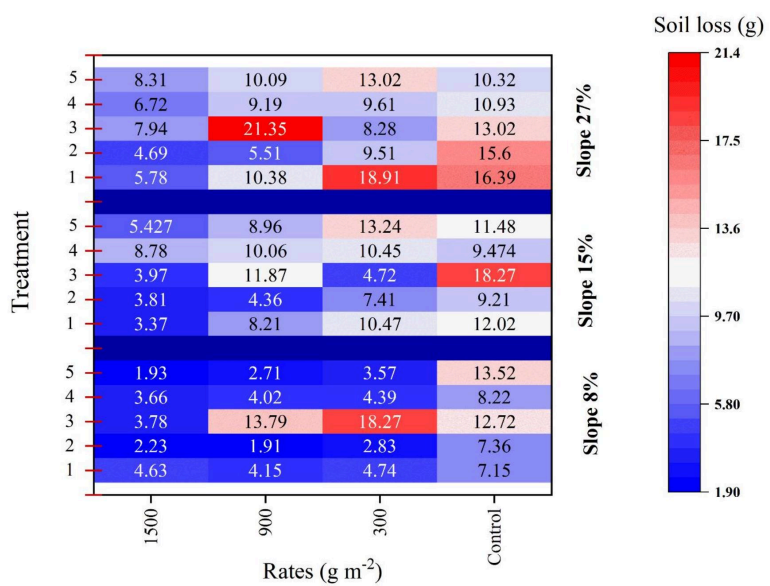


Fig .3 Comparative distribution of the soil loss values of different treatments at different slopes (i.e., 8, 15, and 27%) and rates (i.e., 300, 900, and 1500 g m^{-2})

Figure 3

See image above for figure legend.

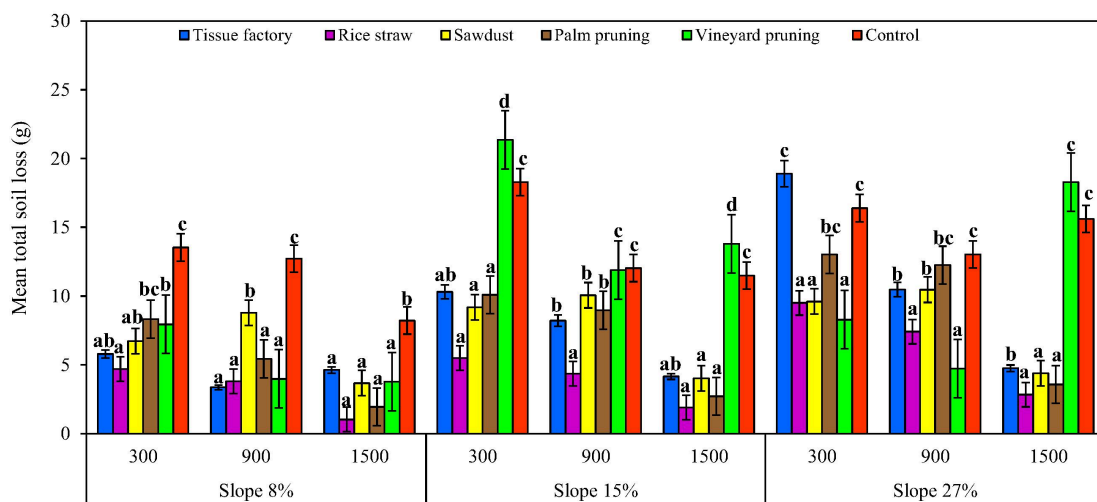


Fig. 4 Comparative chart of mean total soil loss (g) and mean standard deviation in experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from various raw materials at different slopes (i.e., 8, 15, and 27%)

Figure 4

See image above for figure legend.

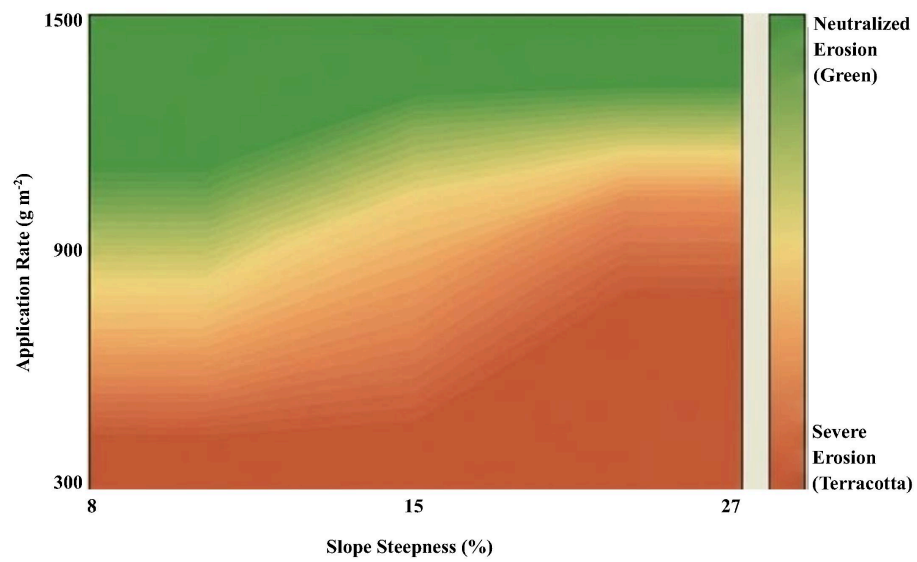


Fig. 5 The optimization curve neutralizing the slope penalty at different application rates (i.e., 300, 900, and 1500 g m⁻²) and slopes (i.e., 8, 15, and 27%)

Figure 5

See image above for figure legend.

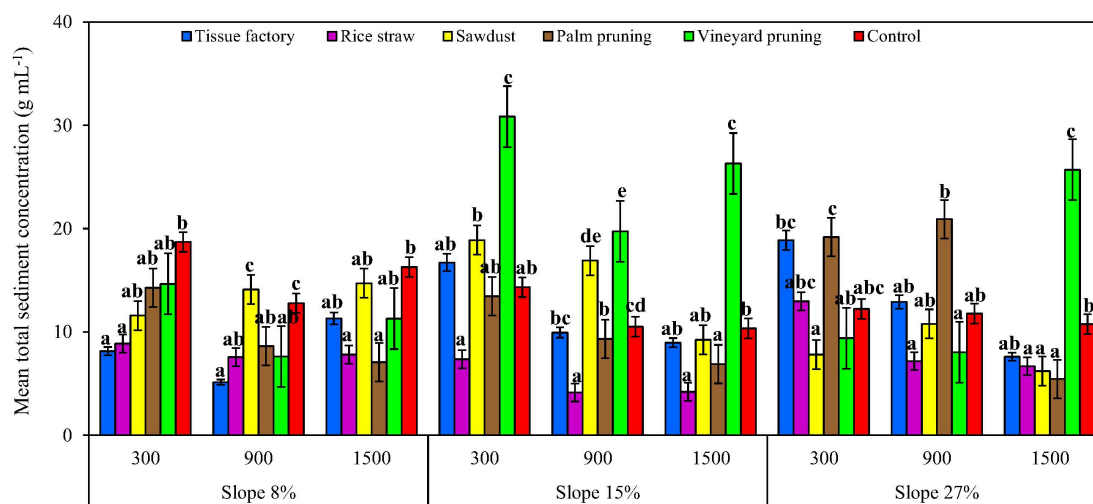


Fig. 6 Comparative chart of mean total sediment concentration (g) and mean standard deviation in experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from various raw materials at different slopes (i.e., 8, 15, and 27%)

Figure 6

See image above for figure legend.

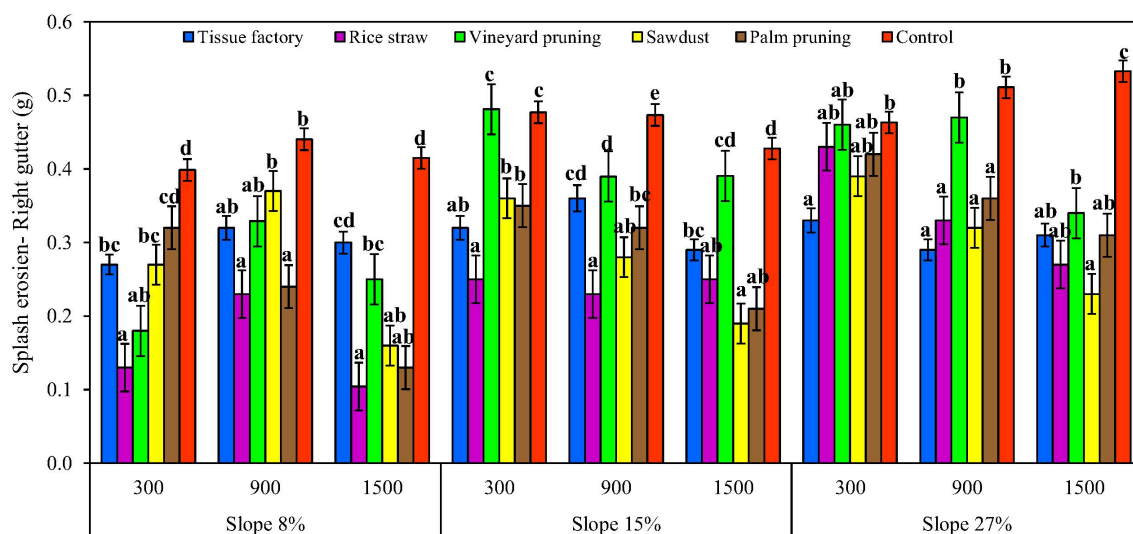


Fig. 7 Comparative chart of mean splash erosion-right gutter (g) and mean standard deviation in experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from various raw materials at different slopes (i.e., 8, 15, and 27%)

Figure 7

See image above for figure legend.

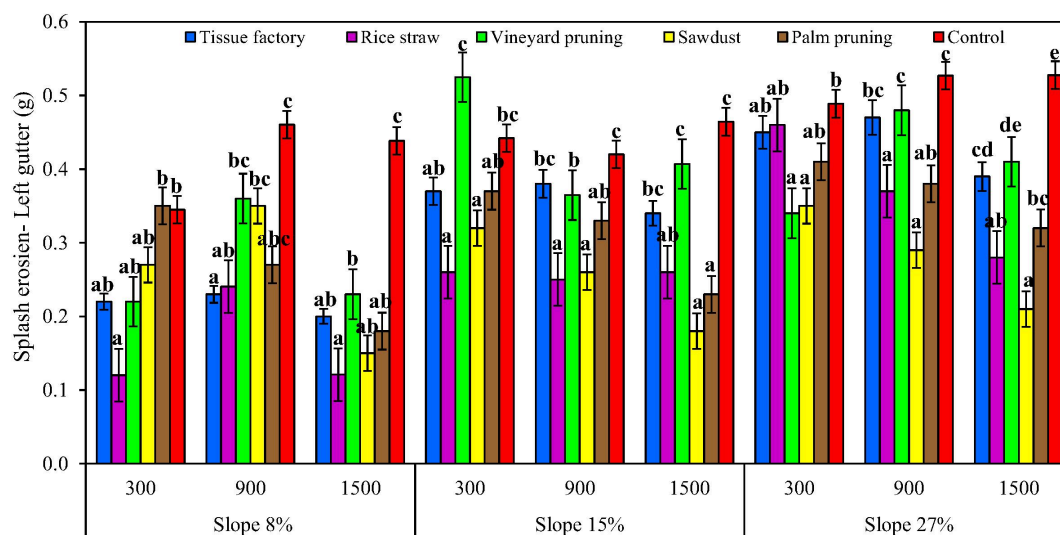


Fig. 8 Comparative chart of mean splash erosion-left gutter (g) and mean standard deviation in experimental small plots under three application rates (i.e., 300, 900, and 1500 g m⁻²) produced from various raw materials at different slopes (i.e., 8, 15, and 27%)

Figure 8

See image above for figure legend.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [HighlightsOriginal.docx](#)
- [GraphicalAbstractOriginal2.docx](#)