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Splash erosion control in saline soils through harnessing agricultural waste-derived engineered porous carbon

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ABSTRACT

Splash erosion is a primary driver of soil degradation, necessitating innovative management solutions that integrate waste recycling. This study evaluated the effectiveness of engineered porous carbon (modified biochar), derived from sawdust, rice straw, and palm pruning residues, in mitigating runoff erosion and enhancing aggregate stability in saline soil under simulated rainfall. Biochars were synthesized via pyrolysis at 400 °C, followed by chemical activation with KOH at 800 °C. These materials were applied at a 5% (w/w) ratio to soil plots with a 10% gradient and subjected to simulated rainfall (70 mm h^{-1} for 30 min). The empirical findings from splash erosion measurements using a pair of side-nested gutters revealed that the application of all porous carbon variants significantly ($P \leq 0.05$) attenuated splash erosion rates relative to the untreated control. The sawdust-derived biochar exhibited the highest mitigation performance, decreasing particle splash detachment by 60% in the right gutter and 59% in the left gutter. Concurrently, soil aggregate stability was remarkably enhanced in the rice straw (55.33%), sawdust (42.20%), and palm pruning (37.34%) treatments compared to the control (28.31%). The highly developed porous structure of these materials successfully dissipated raindrop kinetic energy, preventing surface sealing and crusting. This study demonstrates that engineered porous carbon derived from agricultural waste is a highly efficient, dual-purpose strategy for sustainable waste management and the reclamation of vulnerable saline terrains. Given its dual environmental value in erosion control and waste recycling, this approach is strongly recommended for the sustainable management of saline landscapes.

Keywords: Aggregate stability, Engineered biochar, Rainfall simulator, Splash erosion, Splash gutter

INTRODUCTION

Rain erosion is a highly complex natural process driven by raindrop splashing and runoff leaching, with physical effects such as local impact and fine-particle dispersion caused by splashing (Ao et *al.,* 2019). With the exacerbation of global climate change and concomitant shifts in precipitation regimes, the intensity of erosive forces has increased markedly, precipitating severe ramifications such as severe depletion of soil fertility, degradation of soil structural integrity, and imminent threats to global food security (Spandana *et al.,* 2026). Under these conditions, splash erosion is the initial stage of soil erosion. It plays a prominent role in the formation and evolution of water erosion, which includes the sequential processes of soil aggregate crushing and the displacement of soil surface fragments over short distances (Li *et al.,* 2023). This specific erosive mechanism is recognized as the most critical stage of soil surface degradation. The direct impact of raindrops on the soil surface, particularly in regions with poorly structured, unstable aggregates and sparse vegetative cover, results in a substantial transfer of kinetic energy to the surface. This process triggers particle detachment and the catastrophic collapse of soil aggregates (Fernández-Raga *et al.,* 2017), which occurs with significantly greater intensity in saline soils due to their inherently brittle nature. Rain splashing not only causes the loss of the surface layer of soil but also reduces permeability by forming physical crusts on the surface, thereby increasing surface runoff and rill erosion (Gholami *et al.,* 2013). Decoupling raindrop splash from runoff-driven erosion is crucial for diagnosing the underlying processes and mechanisms governing soil erosion (Wei *et al.,* 2023). A complex interplay between rainfall characteristics and the soil's intrinsic physical attributes governs the magnitude of splash erosion. The kinetic energy of falling raindrops acts as the primary driver of particle detachment (Aghabeigi Amin *et al.,* 2014; Fu *et al.,* 2020).

Among various highly vulnerable ecosystems, saline soils exhibit an extraordinary susceptibility to erosive forces owing to their unique physicochemical attributes (Wang *et al.,* 2025). In these environments, the high concentration of soluble salts disrupts the electrostatic equilibrium among soil colloids, thereby exacerbating clay dispersion. Consequently, the structural stability of soil aggregates is severely compromised, rendering the soil matrix exceptionally fragile under mechanical stresses. In saline soils, due to the profound reduction in structural resistance, even moderate rainfall intensities can provoke widespread particle displacement. Consequently, identifying highly efficient strategies to reinforce surface soil stability against raindrop kinetic energy constitutes a strategic imperative in the management and conservation of saline terrains.

Biochar is a carbonaceous material synthesized via the pyrolysis of organic biomass under oxygen-limited conditions, exhibiting diverse physical and chemical properties that depend closely on the precursor feedstock, pyrolytic temperature, and processing methodologies (Zhu *et al.,* 2025). This material typically possesses a high specific surface area, a well-developed porous architecture, abundant surface functional groups, and a relative recalcitrance within the soil matrix. These attributes enable biochar to exert highly positive effects on various soil properties, including aggregate stability, water retention capacity, cation exchange capacity (CEC), biological activity, and nutrient bioavailability (Sadeghi *et al.,* 2020; Lu *et al.,* 2024; Ghorbani and Amirahmadi, 2024). From an erosional perspective, biochar may mitigate raindrop-induced particle detachment by increasing surface roughness, enhancing inter-particle bonding, promoting infiltration, and suppressing colloidal dispersion (Sadeghi *et al.,* 2018; Sun *et al.,* 2018; Li *et al.,* 2025; Gholamahmadi *et al.,* 2025; Sharma *et al.,* 2026). Nevertheless, not all biochars exhibit uniform performance.

Expanding knowledge about biochar potential and soil functions can change the status of soil production and evolution, because various biochar pyrolysis processes and their application strategies in saline soil can directly change the dynamic structure of saline soil through the induction of functional groups, carbon bonding, and rearrangement of soil particles (Ghorbani and Amirahmadi, 2024). However, given the coexistence of drought, water scarcity, and soil erosion in arid and saline areas, a product with a high specific surface area and greater porosity has attracted researchers' attention as a modified biochar method, and there is insufficient research on modified biochar concerning specific goals.

Advancements in modern materials engineering now enable the precise tailoring of carbonaceous structures, thereby substantially increasing their specific surface area and generating an abundance of micropores (Pérez-Mayoral *et al.,* 2019). In fact, raw biochar may have a lower capacity than modified biochar. Morph-Genetic Porous Carbon (MGPC) is a modified biochar that enhances the performance of biochar in terms of porosity, water content, and soil chemical and physical properties through precise tuning and functional composition. Porous carbon or modified biochar usually has higher porosity, greater surface area, and stronger ion-adsorption capacity, thereby improving soil physical properties (Sadeghi *et al.,* 2026). These properties can be particularly important in saline soils, as such materials may partially counteract the negative effects of sodium by increasing porosity and improving soil structure, and increasing the resistance of the soil surface to rain impact. This process leverages the advantages of porous carbon materials and enhances MGPC's effectiveness for soil improvement. MGPC, with excellent properties, is rarely used, and there is no targeted research to improve it and reduce splash erosion in saline soils. Accordingly, the present study evaluates MGPC's ability to improve the efficiency of saline lands by reducing splash erosion and preventing soil erosion under laboratory conditions using a rain simulator.

On the other hand, biochar production from agricultural, industrial, or waste biomass is not only a soil amendment but also a clear example of waste management and a circular economy approach. In this approach, waste materials are converted into value-added products rather than being disposed of or incinerated, thereby contributing to both soil protection and reduced environmental impact. Therefore, using waste to produce porous carbon is both environmentally and economically significant and can play an important role in the development of sustainable agriculture.

The present study, therefore, aimed to (1) evaluate the capability of the three types of morphogenetic porous carbons produced by the pyrolyzing of sawdust, rice straw and palm pruning residues to reduce splash erosion in a saline soil under simulated rainfall conditions; (2) quantify the effects of these different amendments on soil aggregate stability; (3) compare the effectiveness of each of the three types of biochar to an untreated control to determine which one will reduce splash erosion the most and improve aggregate stability, and (4) test the dual-purpose potential of these waste-derived porous carbons as both a sustainable waste management solution and a soil aggregate stabilizer for sensitive saline soils.

MATERIALS AND METHODS

Preparation of porous carbon

In this study, to prepare porous biochar, waste from straw, palm pruning, and sawdust was collected in the required amounts. Then they were converted into small pieces and dried using a chipper. After that, the initial biochar was prepared at a temperature of 400 °C in a furnace under oxygen-free conditions, then the crushed and sieved biochar was mixed using KOH activator in a ratio of 1:1, and the required amount of water was added, and converted into porous biochar at a temperature of 800 °C under nitrogen (N_2) gas conditions. The resulting porous biochar was crushed and sieved after cooling, yielding the required product ready for use (Sadeghi *et al.,* 2026).

Study area and soil sampling

The bulk soil matrix required for the simulated rainfall experiments was collected from the surface layer (depth of 0-20 cm) of saline terrains located in Incheh Borun, Golestan Province, Northern Iran. According to regional pedological surveys, the soils in the study area are classified as Solonchaks, characterized by poor drainage, extreme salinity, and electrical conductivity (EC) ranging from 2 to 50 dS m^{-1}. The predominant soil texture ranges from medium to heavy, with a shift toward silty loam. Based on long-term meteorological data from the Incheh Borun station, the mean annual precipitation and mean daily temperature are reported as 250 mm and 17.06 °C, respectively, and the soil texture is silt loam to silt clay loam (Ehsani *et al.,* 2017).

To conduct rain simulation experiments, about two tons of soil were collected from designated points in the area and, after initial sieving and separation, prepared for constructing erosion plots. The prepared soil was packaged in plastic bags and then in sacks to maintain soil moisture in the area, and was transported to the Rainfall and Erosion Simulation Laboratory at the Faculty of Natural Resources, Tarbiat Modares University.

Experimental design and plot preparation

The simulation experiments were executed utilizing cubic erosion plots with surface dimensions of 0.5 × 0.5 m, a depth of 0.3 m, and a total volumetric capacity of 0.075 m^3, located at the Rainfall and Erosion Simulation Laboratory of Tarbiat Modares University. These specific plot configurations were selected to precisely regulate temperature and moisture dynamics, circumvent technical limitations, and mitigate the substantial logistical costs of transporting bulk soil from the study site. The preparation of the soil profile within the plots strictly adhered to the methodological protocol established by Sadeghi *et al.* (2021). Thus, first, a layer of mineral pumice with varying stratifications, about 10 to 15 cm thick, was placed on the bottom of the plots to ensure proper drainage and achieve the greatest similarity to natural conditions. To increase friction along the sides of the plot and to prevent an increase in runoff velocity at the border between the soil and the plot wall, a layer of hemp sack was placed as a separator between mineral pumice and soil. After preparing the raw materials and converting them into porous carbon, the experimental treatments considered for the upcoming research included three types of MGPC with a surface area of 5% by weight of soil (Sadeghi *et al.,* 2026) and three replications and a control treatment with an average slope of the area of 10%.

Fig. 1. Steps in preparing experimental plots
Sieving soil (1), pouring pumice and placing a layer of hemp sack in the plots (2), preparation (3), and a sample of the prepared plot (4)

The MGPC was uniformly mixed with the soil in the desired amount under conditions similar to those in the field, ensuring a relatively uniform distribution. Then, soil was placed to a thickness of about 10-15 cm in the upper part of the plots, so that the soil surface was level with the overflow surface of the plots. After the treatments were prepared, the plots were kept in the same state for four days before the simulation. The plots' surfaces were also covered with plastic to prevent precipitation during this period. Fig. 1 shows the stages of experimental plot preparation and the mixing of MGPC with soil in the plots.

Rainfall simulation and splash erosion measurement

In the present study, based on the intensity-duration-frequency (IDF) curves extracted from the Incheh Borun pluviograph station and meteorological assessments from the Golestan Province Meteorological Organization, a design rainfall intensity of approximately 70 mm h^{-1} with a 30-min duration and a 30-year return period was established. To accurately quantify splash erosion, two splash gutters were positioned a few centimeters above the soil surface, covering approximately 14% of the total plot area across all treated and control experimental units (Sadeghi and Parvizi, 2022).

For this purpose, after the rain simulation in each experimental stage ended, runoff samples from the right and left gutters were left stationary for 24 h to allow sediment to settle. Then the water was slowly drained onto the settled sediment. The sediment samples, along with the excess runoff, were poured into metal containers of a known weight and dried in a thermal oven at 105 °C for 24 h. Finally, the dried sediment samples were weighed using digital scales with an accuracy of 0.0001g (Gharemahmudli and Sadeghi, 2024; Gharemahmudli and Sadeghi, 2025). Soil stability was also measured using the Pojasok and Kay and (1990) method. Fig. 2 shows the steps for preparing and measuring splash erosion in plots.

Statistical analyses

Following execution of the three experimental replicates, a comprehensive database of data collected from both the left and right splash gutters was compiled in Excel 2016. The normality of the data distribution was rigorously evaluated using the Shapiro-Wilk test, and the homogeneity of variances was assessed using Levene's test. For datasets exhibiting a non-normal distribution, a logarithmic transformation (log10) was applied to satisfy the assumptions of normality (Lix *et al.,* 1996). To assess the statistical significance of the applied treatments and identify the optimum amendment

Fig. 2. Steps in measuring splash erosion
Installation of splash gutters (1 and 2), sediment washed from gutters (3)

configurations, a one-way analysis of variance (ANOVA) was performed. Consequently, upon detecting significant differences among the treatment efficiencies, post hoc mean comparisons were conducted using Duncan's multiple range test, which was deemed the most appropriate, robust method for segregating group means (Tabachnick and Fidell, 2013). All inferential and descriptive statistical analyses were performed using SPSS 23, with statistical significance set at Pd"0.05.

RESULTS AND DISCUSSION

Results of splash erosion measurements

To evaluate the effect of porous carbon on splash erosion in the study and control treatments, the amounts of right and left splash were measured using splash gutters after rainfall began. The results and statistical criteria for splash erosion in the study treatments at the 5% weight level and a 10% slope are presented in Tables 1 and 2.

The statistical inferences presented in Tables 1 and 2 indicate that incorporating distinct porous carbon variants had a highly significant ($P<0.05$) mitigating effect on rain-induced splash erosion, resulting in a pronounced reduction in sediment displacement across all amended plots relative to the untreated control. Within the control plot treatment, the mean splash erosion rates recorded for the right and left gutters were 0.35 and 0.39 g, respectively, representing the maximum erosive loss among all experimental treatments. Conversely, the minimum

Table 1. Splash values (g) from rain simulation on study plots

Treatments	Replications and descriptive statistics	Splash amounts (g)	
		Right gutter	Left gutter
Sawdust	1	0.14	0.16
	2	0.12	0.13
	3	0.17	0.18
	Mean	0.14	0.16
	Standard deviation	0.02	0.02
	Coefficient of variation (%)	15.69	13.11
Palm pruning	1	0.30	0.24
	2	0.26	0.19
	3	0.16	0.31
	Mean	0.24	0.25
	Standard deviation	0.06	0.05
	Coefficient of variation (%)	24.61	18.94
Rice straw	1	0.19	0.22
	2	0.21	0.19
	3	0.16	0.18
	Mean	0.19	0.20
	Standard deviation	0.02	0.02
	Coefficient of variation (%)	11.01	8.20
Control	1	0.35	0.40
	2	0.43	0.38
	3	0.28	0.39
	Mean	0.35	0.39
	Standard deviation	0.06	0.01
	Coefficient of variation (%)	17.58	2.65

Table 2. Results of One-Way ANOVA analysis of variance to detect the unilateral effects of study treatments

Gutter	Change resources	Degrees of freedom	Significance level	F-statistic	Mean square
Right	Between Group	3	0.025	8.164	0.008
	Within Group	8	0.003		
	Total	11			
Left	Between Group	3	0.031	25.951	0.000
	Within Group	8	0.001		
	Total	11			

splash displacement was consistently observed in the sawdust-derived porous carbon treatment, exhibiting mean values of 0.14 g in the right gutter and 0.16 g in the left gutter.

The percentage reduction in splash erosion relative to the control showed that the sawdust treatment reduced erosion by 60% in the right gutter and 59% in the left gutter. Also, straw and rice straw treatments reduced runoff by 46 and 49%, respectively, and palm pruning residue treatments reduced splash erosion by 31 and 36%, respectively. The splash rate in the sawdust treatment was about 2.5 times lower than the control; in the straw and rice straw treatments, it was about 2 times lower, and in the palm pruning residues treatment, it was about 1.5 times lower than the control. The results of this study showed that amending saline soils with biochar from waste significantly ($P<0.05$) reduces the runoff erosion rate (Table 2).

Porous biochar increases soil surface roughness and reduces the impact speed of raindrops due to its high porosity. Sadeghi *et al.,* (2026), in a study examining the Brunauer–Emmett–Teller (BET) surface area of conventional and porous biochar, concluded that porous biochar treatments exhibit a much higher specific surface area and porosity than conventional biochar. Similarly, the presence of fine and coarse pores in the porous biochar structure absorbs part of the drops' impact energy, preventing it from being transferred to the soil. This reduction in the splashing rate is directly related to improved aggregate stability (Fig. 3).

Our results showed that soil stability was significantly increased in the treatments of straw and stubble (55.33%), sawdust (42.20%), and palm pruning (37.34%) compared to the control (28.31%). These results are consistent with studies by Laird *et al.,* (2010), who reported that biochar serves as a central nucleus for the formation of stable aggregates and increases soil resistance to mechanical stresses by enhancing organo-mineral interactions. Biochar increases soil resistance to segregation by enhancing soil aggregate stability and improving particle bonding (Sadeghi *et al.,* 2016; Shi *et al.,* 2022), thereby reducing the number of particles detached and transported by splashing. Additionally, Lu *et al.,* (2024) stated that the main mechanism of biochar as a soil amendment is to increase particle adhesion and improve aeration, thereby increasing soil resistance to the mechanical forces of rain. They stated that the formation of macroaggregates can effectively prevent soil flaking caused by clay

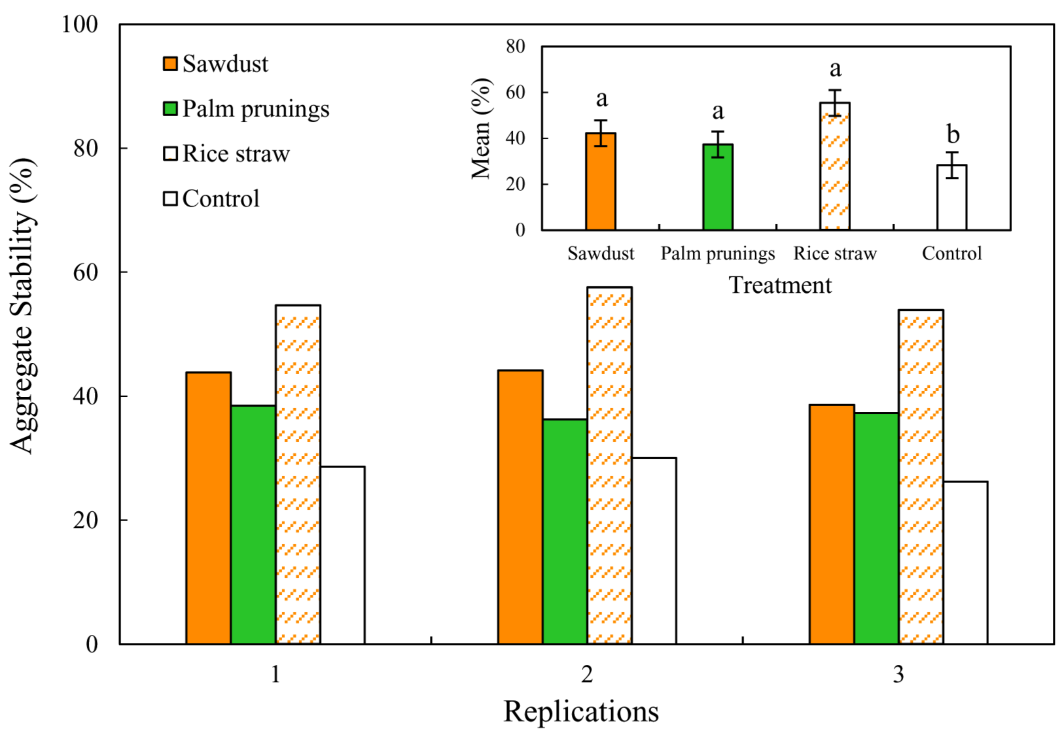

Fig. 3. Results of measured soil aggregate stability (%) and associated statistical comparison (sub-figure in upper right) in study treatments

dispersion and provide larger pores for water and air flow, thereby increasing permeability (Hseu *et al.,* 2014; Wang *et al.,* 2017; Gholamahmadi *et al.,* 2023).

Modified porous carbon exhibits greater cation exchange and ion adsorption capacities in saline soils, thereby enhancing soil defense mechanisms against erosion (Ahmad *et al.,* 2014). Biochar improves soil particle stability, absorbs the impact energy of raindrops, and prevents particle splashing (Khademalrasoul *et al.,* 2019).

The reduction in splashing observed in biochar treatments is also consistent with findings from previous studies. Sadeghi *et al.,* (2020) showed that using biochar derived from vinasse significantly reduces splash erosion in loess and marl soils. Gholamahmadi *et al.*, (2025) also confirmed the reduction of splashing erosion with biochar in sloping sandy loam soils. The biochar used in this study has a distinctive porous structure (Sadeghi *et al.,* 2026), which likely increased its impact energy absorption capacity and surface roughness compared to many biochars used in previous studies.

In addition to its physical role in reducing the kinetic energy of rain, the amendment role of biochar in saline soils is vital. In saline soils, the high concentration of sodium ions (Na^+) increases the dispersion of soil aggregates and, as a result, sharply decreases their stability. Biochars, with their high cation exchange capacity (CEC) and porous structure, can mitigate the destructive effects of sodium on soil structure by retaining cations and restoring electrochemical balance. This allows soil aggregates to resist the hydraulic pressure of raindrops despite the presence of salts and prevents the formation of a hard surface layer (Surface Sealing), which is very common in saline soils.

However, some studies have shown that the effect of biochar on erosion is not always a reduction. For example, Wei *et al.,* (2023) reported that under certain laboratory conditions and at high application rates, biochar can increase splash erosion due to increased removable particles and changes in soil hydraulic properties. This difference in results is likely related to differences in soil type, biochar production source, particle size, application rate, and rainfall intensity. Therefore, it can be concluded that the effectiveness of biochar in erosion control depends on its physical properties and environmental conditions, and optimizing these factors plays a decisive role in its success.

CONCLUSION

This study showed that using biochars derived from waste is an effective means of reducing splash erosion in saline soils. The results showed that biochar, by improving the stability of soil aggregates, increases soil resistance to salinity-induced dispersion and, as a result, significantly reduces the rate of splash erosion by absorbing the kinetic energy of raindrops. Charcoal derived from sawdust showed the highest efficiency in controlling splash, and charcoal derived from straw and stubble showed the highest efficiency in improving structural stability. This approach, while managing waste, can prevent the physical degradation of saline lands caused by heavy rainfall. This research demonstrated that soil amendment with biochars derived from different waste streams is a dual and efficient solution for environmental management. The findings showed that although each type of waste has different characteristics regarding splash control or structural stability, they all control erosion better than unamended soils. The use of this technology can be proposed as a soil management strategy in programs aimed at combating desertification and protecting agricultural lands from the impacts of climate change.

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