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Short-Term Effects on Rill Erosion and Flow Resistance in a Wood-Biochar Amended Soil

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ABSTRACT

Despite growing interest in biochar as a soil amendment, its effects on erosion control remain uncertain, particularly for rill erosion. In this investigation, the short-term (i.e., 1 month after biochar addition) effects of wood-biochar on rill erosion and flow resistance were evaluated. At first, plot experiments were performed discharging a constant clear inflow into a rill incised in the original soil (rill₀) and two rills, named rill₃ and rill₅, incised in clay loam soil amended with different initial biochar concentrations *BC* (3% and 5% by weight). For each rill, the outflow discharge of the entire run was collected by a storage tank and the run was stopped when a 55 L volume was reached. The collected volumes were used to measure the corresponding weights of the eroded mixture (sediments and biochar), biochar and sediments. 3D photo reconstruction was used to obtain the Digital Elevation Models (DEM) before and after the runs and by the corresponding DEM of difference, the total volume of the eroded mixture was calculated. Measurements of water depth, hydraulic radius and flow velocity were used to calculate the Darcy–Weisbach friction factor *f* values. The results demonstrated that in the short term, the addition of *BC* = 3% is effective in reducing soil erosion by 9% as compared to the control condition, while adding *BC* = 5% determined an increase of 140% in eroded volume as, for this latter, the short-term soil particle aggregation effects are too weak and the mixture remains cohesionless. Moreover, the analysis demonstrated that the proposed flow resistance equation gives a reliable *f* estimate and this equation gives, for fixed hydraulic conditions, flow resistance that decreases with increasing *BC*. Ultimately, for the short term, *BC* higher than 3%–4% cannot be considered a good soil conservation practice.

1 | Introduction

Soil erosion is a significant environmental issue affecting many regions of the world (Borrelli et al. 2017; Carollo et al. 2023), whose effects are exacerbated by human activities and whose relevance is highlighted by several field investigations (Bagarello et al. 2008, 2011, 2018). The process of soil formation is extremely slow, while its use and anthropogenic actions produce accelerated soil loss. Soil erosion processes determine both on-site (e.g., reduction of soil fertility and productivity) and off-site

(e.g., deposition of sediments in rivers and artificial reservoirs) effects (Di Stefano et al. 2023, 2016).

Rill erosion is the result of soil detachment and particle transport by channelised flows, which are characterised by higher flow shear stress, velocity and sediment yield values. Rills are mobile bed channels with rapid morphological changes (Di Stefano et al. 2022a), represent a relevant sediment source and dominate hillslope sediment transport (Mutchler and Young 1975; Zhang et al. 2016). Moreover, the formation of

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a rill network favours the transport of both soil particles detached by rill flow and those delivered from the interrill areas to rills (Bagarello and Ferro 2010; Bagarello et al. 2015; Bruno et al. 2008; Di Stefano et al. 2013, 2015; Govers et al. 2007; Peng et al. 2015).

Farmers generally avoid planting cover crops to reduce soil erosion as they are worried about the competition with the main crop for water and nutrients (Guerra and Steenwerth 2012; Novara et al. 2021) and prefer the use of other soil conservation practices (Telles et al. 2022; Quinton and Fiener 2024). Considering that the use of synthetic additives is restricted or controlled in organic farming, organic amendments, such as biochar or compost, are a valid eco-friendly alternative (Schmidt et al. 2014; Autovino et al. 2026). Since June 2022, EU's fertiliser regulation has also included biochar and since this point it has been possible to produce CE-marked biochar products for use as fertilisers and soil enhancers for the European market (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R1009-20240703> (Thomsen 2024)). Moreover, the potential of biochar addition to soils was also included in the biochar guidance by the Intergovernmental Panel on Climate Change (IPCC) as a basis for future methodological development for United Nations Framework Convention on Climate Change (UNFCCC) signatory countries to quantify their annual greenhouse gas sources and sinks (Ogle 2019; Woolf et al. 2021).

Biochar is produced by pyrolyzing biomass, under controlled conditions of temperature and pressure, in the partial or complete absence of oxygen (Sohi et al. 2010). Generally, biochar positively affects the overall quality of soil (Blanco-Canqui 2017), as it improves soil structure, enhances aggregate stability and organic matter and determines the increase in crop production and quality (Wang and Wang 2019) by modifying soil hydraulic conductivity and water retention capacity (Wani et al. 2023). As a very low degradation rate characterises biochar, the improvements of chemical, physical and biological soil characteristics can be kept for a long time (Atkinson et al. 2010; Castellini et al. 2015). Jiang et al. (2025) conducted a meta-analysis of 61 field studies (2009–2023) to evaluate the mid (1–2 years) and long-term (3–10 years) effects of biochar on soil hydraulic properties across varying conditions. The results showed that biochar application significantly improves soil structure by increasing total porosity, saturated hydraulic conductivity, field capacity and available water capacity, while reducing bulk density. These benefits peak within the first 2 years and gradually decline due to biochar ageing, although positive effects persist beyond 3 years. These authors also highlighted that the magnitude of improvement is strongly influenced by biochar type, application rate and soil texture, with woody biochar and application rates of 20–40 Mg/ha being most effective, particularly in fine-textured soils.

As biochar application exerts positive impacts on the mechanical and hydraulic soil properties and has shown promise as an effective tool for controlling erosion, the overarching effect of biochar has been evaluated in some experimental investigations (Sharma 2024).

Using a rainfall intensity of 80 mm h⁻¹ and a long-term cultivated acidic Ultisol (43.6% clay, 40.2% silt and 16.2% sand), Jien

and Wang (2013) tested the effects of different biochar concentrations *BC* (0%, 2.5% and 5% in weight (100×g biochar/g total soil)). These authors concluded that a reduction of soil loss (50% and 64% at 2.5% and 5% application rates, respectively) occurred in comparison with the non-amended soil condition.

Using a small plot 27% sloping, a rainfall intensity of 90 mm h⁻¹ and a silt loam soil, Li et al. (2019) studied the biochar addition effects on soil erosion phenomena using four *BC* values (1%, 3%, 5% and 7% in weight) with three different biochar particle sizes (2–1, 1–0.25 and <0.25 mm). The experimental runs allowed for assessing that low *BC* (1% and 3%) inhibits soil loss, while higher *BC* (5% and 7%) promote it.

Li et al. (2020), using the same silt loam soil and experimental layout as Li et al. (2019), established that biochar with coarse particle size (1–2 mm) with *BC* ≤ 3% reduces soil degradation due to erosion processes.

Sadeghi et al. (2016) performed some plot experiments with a slope of 20%, a rainfall intensity of 50 mm h⁻¹ and a sandy clay loam soil amended by vinasse-produced biochar. The application of biochar reduced runoff volume, soil loss and sediment concentration rates.

Zhang et al. (2019) highlighted that contradictions have been observed in the literature about the effects of biochar on soil erosion. In fact, many authors (Abrol et al. 2016; Doan et al. 2015; Hseu et al. 2014; Jien and Wang 2013; Lee et al. 2015; Sadeghi et al. 2016; Smetanová et al. 2013) observed that biochar addition reduces soil erosion, while other authors (Lee et al. 2018; Li et al. 2017, 2019; Peng et al. 2016; Wani et al. 2023) supported the hypothesis that biochar amendment can promote soil erosion.

The experiments by Zhang et al. (2019), carried out with a clay loam soil with a slope gradient of 17%, four simulated rainfall intensities (25, 50, 75 and 100 mm h⁻¹), three biochar concentrations (2%, 5% and 8% by weight) and two incubation periods (no incubation and a 140-day incubation), concluded that the amendment with biochar reduced both the soil bulk density and soil compactness (Busscher et al. 2010; Doan et al. 2015; Herath et al. 2013), increasing the interrill erodibility.

By developing a meta-analysis of biochar impacts on runoff and soil erosion, Gholamahmadi et al. (2023) assessed that the best strategy to mitigate soil erosion could be realised by incorporating biochar into the topsoil (15 cm or less) and using *BC* values between 0.6% and 2.5%. Thus, according to the conclusions by Gholamahmadi et al. (2023), biochar concentrations greater than 2.5% should be useless to reduce soil erosion.

The presented contradictory results can be explained considering the differences due to the investigated soils, the applied biochar type, particle size, bulk density and porosity, the method used for applying biochar (spread over the soil surface, incorporated into the soil), the vegetation growth and the change in physical and chemical soil properties due to biochar amendment (Wani et al. 2023). According to the review by Sharma (2024), the biochar properties are pivotal in influencing erosion intensity in different environments. In fact, the fundamental biochar properties (i.e., particle size, surface

area, bulk density, porosity and chemical composition) significantly affect its effectiveness in erosion mitigation. For instance, biochar with larger particle sizes and increased surface area tends to create a more stable soil structure by reducing the soil susceptibility to erosive forces (Wang et al. 2020). A biochar type characterised by high porosity facilitates water infiltration and retention, minimising surface runoff and soil detachment during rainfall events (Ahmadi et al. 2020). The spreading of biochar on the soil surface (Sadeghi et al. 2016; Smetanová et al. 2013) is characterised by the formation of a biochar surficial layer that protects the soil structure, inhibits seal formation, favours infiltration processes and is constituted of low-density biochar particles characterised by high transportability (Sadeghi et al. 2016). However, field applications are carried out by adding biochar inside the arable soil horizon and thoroughly mixing to favour the improvement of soil properties.

At present, most of the available investigations deal with interrill erosion under simulated rainfall, while few investigations on rill erosion are available (Bagarello et al. 2025; Li et al. 2021, 2025; Nicosia, Pampalone, and Ferro 2021; Parhizkar et al. 2023).

Li et al. (2021) carried out some experimental runs on susceptibility to rill formation using two biochar concentration values ($BC=1.4\%$ and 3%) and observed that this susceptibility decreases with the biochar addition. Parhizkar et al. (2023) investigated the effect of rice husk-biochar on rill erosion by flume experiments with non-amended soil and soil amended with $BC=3\%$ in weight. These authors established that adding biochar reduces rill erodibility and critical shear stress for the investigated silty-clay soil. Li et al. (2025) investigated the impact of biochar on rill erodibility K_r and critical shear stress τ_c in order to establish a relationship between K_r , τ_c and soil properties. In comparison with no biochar addition Li et al. (2025), assessed that the addition of 1% – 4% biochar after 1–2 years (mid-term period) generally determined a reduction of K_r and an increase of τ_c , while the opposite trend was found for $BC=5.5\%$ and 7% . In other words, the addition of 1% – 4% biochar concentration can be considered an effective soil conservation practice able to enhance soil resistance to rill erosion. Moreover, they obtained that for a long-term incubation period (3 years), also the highest biochar concentrations (5.5 and 7%) led to a reduction of K_r and an increase of τ_c , showing an always increasing trend of biochar effectiveness with increasing biochar concentration.

Nicosia, Pampalone, and Ferro (2021), using the data collected by Li et al. (2021) in plots with four slopes (3.1% , 6.3% , 9.4% and 12.6%), demonstrated that the biochar addition reduced the flow Froude number due to the increase in roughness, which determined the decrease in flow velocity and the increase in water depth. The authors highlighted that the increase of biochar concentration (1.4% and 3%) damped the effect of turbulence on rill flow resistance.

Bagarello et al. (2025) investigated the effects of rill formation and biochar addition on the physical and hydraulic properties of a clay-loam soil by using laboratory hydrological measurements and rill formation tests at the plot scale. These measurements demonstrated that the biochar addition to soil improved its aptitude to transmit water. Moreover, their results showed that

rilling altered the soil characteristics for soils without biochar, while the addition of a large amount of biochar ($BC=5\%$) impeded these alterations from occurring.

Conte et al. (2025) performed plot experiments entering a clear inflow into two rills amended with an initial BC (in weight) of 3% and 5% to investigate soil erosion phenomena. In particular, these authors collected three samples of the outflow discharge 2, 8 and 11 min after the beginning of the experimental run. The results highlighted that $BC=5\%$ was more efficient than $BC=3\%$ in mitigating rill erosion phenomena. However, this last study was limited by the lack of the experimental run for the bare soil condition.

In conclusion, although some uncertainties are related to the use of biochar as a soil conservation practice, the available literature regarding biochar effects on both interrill and rill erosion allows for stating that the optimal biochar amount to be applied for reducing runoff and soil loss could be the one corresponding to a BC of 3% – 5% . However, new research is needed to assess this result for rills, for which the available literature is poor and evaluate the dependence between the incubation period duration and the effectiveness of biochar addition against rill erosion. Moreover, the analysis of flow resistance in amended soils needs to be deepened as only one study (Nicosia, Pampalone, and Ferro 2021) is currently available.

The general aim of this study is to experimentally investigate the short-term (i.e., 1 month after biochar addition) effects of wood-biochar on rill eroded volumes and flow resistance in amended soils. In detail, some experimental measurements carried out on rills formed in a clay loam soil amended with two different BC values (3% and 5%) are used with the specific aims to: (i) compare the eroded mixture weights and volumes determined by the same inflow; (ii) analyse the mixtures of eroded sediment and biochar outflowing from the rills to determine the content of sediment and biochar in the eroded mixture for each rill and (iii) testing the applicability of the theoretical flow resistance equation (Equation 1) by the measurements carried out in the rills formed in the amended soils ($BC=3\%$ and 5%).

2 | Materials and Methods

2.1 | Measurements of Rill Erosion and Evaluation of the Sediment and Biochar Components

The experimental runs were performed on a plot 2 m wide and 7 m long, equipped with a storage tank (2 m wide, 0.7 m long and 0.4 m deep). The plot is filled with clay-loam soil (32.7% clay, 30.9% silt and 36.4% sand) reaching a mean plot slope of 15% . This soil was collected in the area surrounding the Department, characterised by a typical Mediterranean climate *Csa* following the Köppen classification (Köppen 1918) and vegetation. For considering field variations, the soil was collected from different points within the area. Soil texture was determined by mechanical dry sieving for coarse fractions and by the hydrometer method (Kroetsch and Wang 2008) for fine size fractions using five samples distributed on the plot surface. Three trenches (Figure 1) (length 5.7 m, width 0.2 m and depth 0.1 m) were dug, removing approximately 100 kg of soil per trench.

The extracted soil was left to air-dry for a week. The gravimetric soil moisture was equal to 12.5%. The soil of the first trench was left unamended and used as a control condition (rill₀), while the soil of the second and third trench was amended with biochar concentration *BC* of 3% (rill₃) and 5% (rill₅), respectively. The used biochar was obtained by the pyrolysis of fresh forest wood chips from untreated logs and is certified according to the EBC (European Biochar Certification) (<https://www.european-biochar.org/cert/bleg-5rq5-5t8s-eqyy/de>). This type of biochar is characterised by high porosity, large surface area and ability of water retention. Moreover, the used wood-biochar was chosen considering that it can be produced by pyrolysis of pruning waste (e.g., in vineyards or orchards) and guarantee low costs and an economic circularity of the production processes. The pre-determined wood-biochar (bulk density = 0.26 g cm⁻³, porosity = 0.65 cm³ cm⁻³) concentrations *BC* of 3% and 5% were reached by adding 300 and

500g of biochar to 10kg of soil in dry weight, corresponding to approximately 11.3 kg in wet weight, considering the measured soil moisture. These concentrations were chosen as the available literature regarding biochar effects on rill erosion established that the optimal biochar amount to be applied for reducing runoff and soil loss could be the one corresponding to a *BC* of 3%–5% (Jien and Wang 2013; Li et al. 2019).

A concrete mixer was used to mix soil and biochar for 1 min and then the amended soil was put back into the trenches and compacted. This mixing phase was also carried out for the extracted soil to be used for the control condition (rill₀) to ensure the same initial soil conditions for the three investigated rills. For each trench, a preferential path (Figure 2a), slightly incised and with two converging sides, was traced on the surface of the 0.2 m wide area. The experimental runs were performed after 1 month, which, according to Joseph et al. (2010) could be considered a reasonable time within which biochar usually starts to modify soil characteristics. In comparison with the incubation periods investigated by Li et al. (2025) (i.e., mid-term = 2 years and long-term = 3 years), the period chosen for this investigation can be considered a short-term one. During the incubation period, the plot was covered by a plastic sheet to avoid exposition to natural rainfalls and external disturbances. For the experimental runs, a clear flow discharge (0.25 L s⁻¹), which shaped the preferential path to an actual rill (Figure 2b), was applied.

For all the three investigated rills, only a single run replicate was performed. This experimental design was adopted due to the availability of only one plot filled with this soil and practical constraints associated with mobile-bed experiments on amended soils subjected to an incubation period, including the complexity and substantial time requirements of recreating the initial experimental conditions (i.e., removal of the amended soil to dig the trenches again with a consequent waste of the biochar previously used,

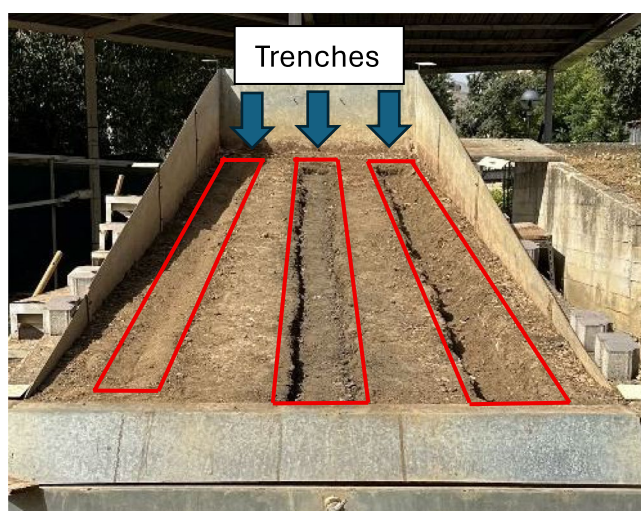


FIGURE 1 | View of the experimental plot with the three trenches.



FIGURE 2 | View of the preferential path (a) and flow moving in the rill (b).

performing the mixing phase of new soil and biochar and waiting for the finish of the incubation period) and conducting repeated runs.

Before the experimental runs, for each rill two samples were collected at the upstream area of the trench by a steel cylinder (diameter and height of 5 cm) to determine the initial soil (both unamended and amended) bulk density, which resulted equal to 1.23, 1.12 and 1.02 g cm⁻³ for rill₀, rill₃ and rill₅, respectively. These values demonstrate that the biochar determines a reduction in amended soil bulk density as compared to the original soil.

For each rill, the outflow discharge of the entire run was collected by the storage tank and each experimental run was stopped when a 55 L volume was reached. The total collected volume (water, sediment and biochar) for each rill was oven-dried at 105°C for 48 h and then weighed to determine the

amount of eroded mixture W_m (kg) (only sediment for rill₀ and sediment and biochar for rill₃ and rill₅). From the total volumes of rill₃ and rill₅, a sub-sample of 30 g was collected by a rotating laboratory mixer to guarantee the homogeneity of the sub-samples. Being the biochar made of organic matter, the total organic matter was burned by putting these sub-samples in a muffle furnace at 400°C and determining the loss on ignition LOI (%). The organic matter OM (%) of the undisturbed soil, determined by two samples subjected to the same procedure, was equal to 2%. The biochar concentration BC_m in the mixtures (i.e., the ratio between the biochar weight W_b and W_m) was determined by subtracting this baseline value from the LOI . Therefore, by multiplying these BC_m values and the corresponding W_m , the biochar weight W_b (kg) of each of the two investigated condition (rill₃ and rill₅) was calculated. Finally, the sediment weight W_s of each rill was calculated as the difference between W_m and W_b . Of course, for the control condition, the W_s value was equal to the W_m one.

A set of approximately 70 photographs taken from the plot area by a digital camera was used to create the three-dimensional Digital Terrain Model (3D-DTM) by a 3D-photo reconstruction technique. From the 3D-DTM, the Digital Elevation Models (DEM) before (D1) and after the experimental runs (D2) were obtained. The total eroded mixture volumes, V_0 for rill₀, V_3 for rill₃ and V_5 for rill₅, were calculated by the DEM of difference (DoD) between D2 and D1.

For each rill, D1 and D2 were also used to determine the corresponding rill thalweg profiles, which were used to obtain the scour depth values SD (i.e., the differences in height between the longitudinal profile for D1 and D2). From the D2 thalweg, the mean slope of each rill s was obtained.

At the end of the run, a dye was used to identify the water tracks inside the channel (Figure 3). The technique presented by Di Stefano et al. (2019), which combines the rill survey with that of the tracks inside the rill, was used to calculate the mean water depth h and hydraulic radius R values.

For each rill, a single measurement of surface flow velocity was performed for the whole rill channel by using a Methylene blue solution as a dye tracer (Di Stefano et al. 2020; Nicosia, Di Stefano, et al. 2021). The obtained values were corrected by a factor of 0.8 (Di Stefano et al. 2021; Zhang et al. 2010) to calculate the mean flow velocity V . The Darcy–Weisbach friction factor was calculated as $8(u_*'/V)^2$. For the investigated environmental conditions, the kinematic viscosity ν_k was equal to 1.27×10^{-6} . Table 1 lists the main hydraulic and geometric variables of each rill.



FIGURE 3 | Water tracks inside the channels marked by using a Methylene blue solution as a dye tracer.

TABLE 1 | Values of flow depth (h), hydraulic radius (R), mean flow velocity (V), slope (s), Reynolds number (Re), Froude number (F) and Darcy–Weisbach friction factor (f) of the three experimental conditions.

BC (%)	h (m)	R (m)	V (m s ⁻¹)	s	Re	F	f
0	0.0079	0.0067	0.393	0.151	2436	1.41	0.518
3	0.0082	0.0068	0.461	0.151	2970	1.62	0.377
5	0.0100	0.0075	0.402	0.146	3168	1.28	0.529

2.2 | Flow Resistance Equation for Amended Soils

Nicosia, Pampalone, and Ferro (2021), using the measurements by Li et al. (2021), proposed the following theoretical flow resistance equation:

$$f = 8 \left[\frac{2^{1-\delta} Re^\delta}{(\delta+1)(\delta+2)} \Gamma_v \right]^{-2/(1+\delta)} \quad (1)$$

where f is the Darcy–Weisbach friction factor, $\delta = 1.5 / \ln Re$ (Barenblatt 1991; Castaing et al. 1990), $Re = Vh/\nu_k$ is the flow Reynolds number (in which V is the mean flow velocity, h is the water depth and ν_k is the kinematic viscosity) and Γ_v is the parameter of the flow velocity power profile (Carollo et al. 2021; Nicosia, Pampalone, and Ferro 2021) defined as follows:

$$\Gamma_v = \frac{V}{u_* \left(\frac{u_* \alpha h}{\nu_k} \right)^\delta} \quad (2)$$

in which α is a coefficient (< 1) considering that V is located under the water surface and the mean velocity profile in the cross-section is referred to and $u_* = \sqrt{gRs}$, where g is the acceleration due to gravity, R is the hydraulic radius and s is the bed slope.

According to Nicosia, Pampalone, and Ferro (2021), the following equation to estimate Γ_v can be used:

$$\Gamma_v = a \frac{F^b Re^e}{s^c} \quad (3)$$

in which $F = V / \sqrt{gh}$ is the flow Froude number, b and c are two coefficients equal to 0.6397 and 0.849, respectively, and a and e are two coefficients that can be estimated by the following equations:

$$a = 0.0276 + 0.0077BC \quad (4)$$

$$e = 0.2118 - 0.0255BC \quad (5)$$

in which BC is expressed as a percentage.

3 | Results

3.1 | Rill Erosion in Biochar-Amended Soils

The values of W_m , W_b and W_s are listed in Table 2.

For increasing BC , the comparison between the mixture weights W_m corresponding to $BC=0\%$ and 3% does not show appreciable differences, while an increase of W_m is detected for $BC=5\%$ (Figure 4a).

TABLE 2 | Weights of the eroded mixture (W_m), biochar (W_b), sediment (W_s) and total eroded volumes (V_r) of the three experimental conditions.

BC (%)	W_m (kg)	W_b (kg)	W_s (kg)	V_r (L)
0	2.35	0.000	2.35	1.47
3	2.23	0.092	2.14	1.023
5	5.84	0.187	5.65	3.53

Figure 4b shows that the biochar weight W_b increases with the initial biochar concentration. However, these biochar weights correspond to a biochar concentration in the mixture BC_m of 4.1% and 3.2% for rill₃ and rill₅, respectively. Consequently, the sediment concentrations in the mixture, corresponding to the sediment weight values W_s (Figure 4c) listed in Table 2, are 95.9% and 96.8% of W_m .

The obtained DoD (Figure 5) and the consequent total eroded volume V_r values (Figure 4d) listed in Table 2 highlight that the eroded mixture for the rill₃ is lower than that for the rill₀ incised in the unamended soil and, therefore, this biochar concentration (3%) reduced the rill erosion phenomenon in comparison with the control condition. Instead, the highest biochar concentration (5%) determined a total eroded volume remarkably higher than the abovementioned ones.

It should be noted that the ratio between the values W_m (kg) and V_r (L) (Table 2) is equal to 1.6, 2.18 and 1.66 kg L⁻¹ for rill₀, rill₃ and rill₅, respectively. Therefore, rill₀ and rill₅ are characterised by comparable values of this ratio, while the rill₃ treatment is characterised by a higher value. In other words, the findings show a different mass-to-volume ratio for the $BC=3\%$ treatment as compared with $BC=0\%$ and 5% .

Figure 6, which shows the frequency distribution of the scour depth values SD , highlights that the rills incised in amended soils are characterised by deeper scours as compared to that of the control condition (rill₀).

However, rill₃ has scour depth values closer to those of the control condition rather than those of rill₅. This result is also confirmed by the values reported in Table 3, of the mean scour depth SD_m , the maximum scour depth SD_{max} and the standard deviation of the scour depths $\sigma(SD)$.

While rill₀ and rill₃ are characterised by uniform scours, the analysis pointed out that rill₅ is characterised by localised scours (Figure 7) that mimic the step-pool scheme.

3.2 | Rill Flow Resistance in Biochar-Amended Soils

For the three investigated conditions (rill₀, rill₃ and rill₅) (Figure 5), the available measurements of water depth, hydraulic radius, mean flow velocity and rill channel slope allowed for calculating the Reynolds number, the Froude number and the Darcy–Weisbach friction factor f (Table 1). The f values reported in Table 1 highlight that the treatment with $BC=3\%$ determined a decrease in flow resistance ($f=0.377$) as compared to the control condition (0.518) and treatment with $BC=5\%$ (0.529), which instead are comparable.

Considering that the measurements were carried out for the whole rill channels, for each BC value (0%, 3% and 5%), a single value of these variables is available. For the investigated conditions, the rill flows were always supercritical and turbulent.

For testing the applicability of the theoretical flow resistance law (Equation 1), the measurements of this investigation were

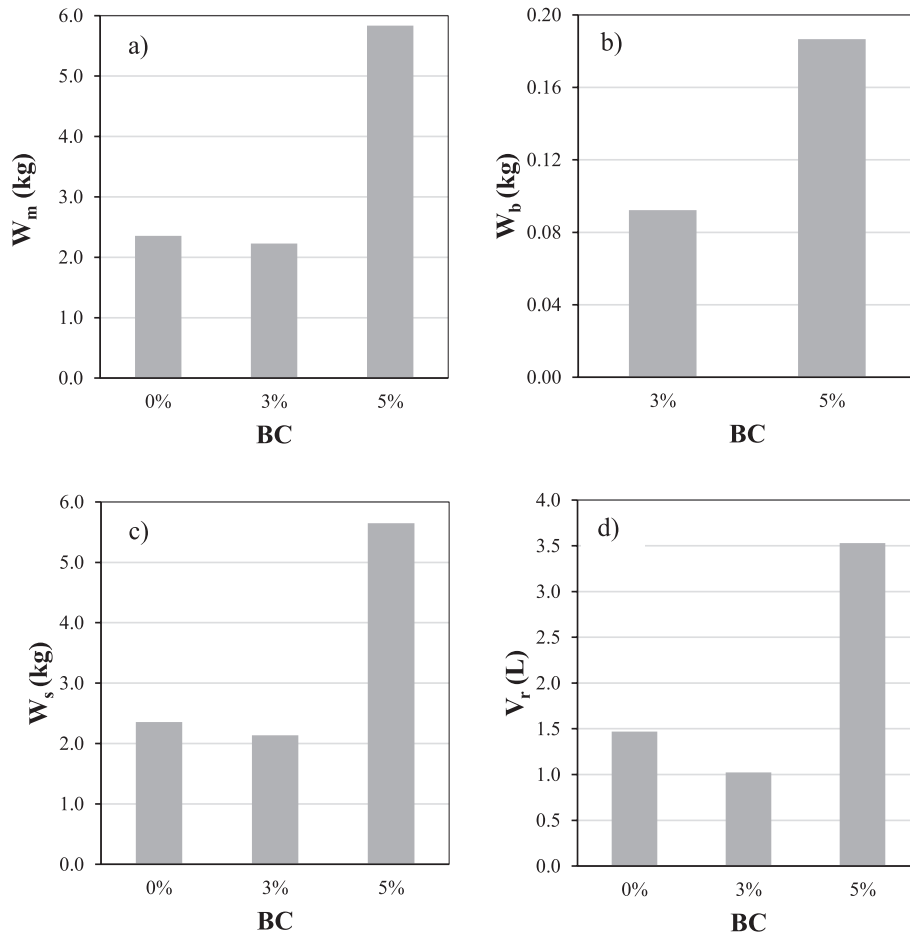


FIGURE 4 | Weights of the eroded mixture (W_m) (a), biochar (W_b) (b) and sediment (W_s) (c) and eroded volumes (V_r) (d) of the three experimental conditions.

joined with the available data by Li et al. (2021). These last measurements were performed by rainfall simulation for a loam soil, four plot slope values (3.1%, 6.3%, 9.4% and 12.6%) and three biochar concentrations BC (0%, 1.4% and 3%). The hydraulic conditions investigated by Li et al. (2021) were characterised by subcritical flow ($0.3 \leq F \leq 0.42$) and transitional and turbulent flows ($508 \leq Re \leq 5718$).

At first, the coefficients a , b , c and e of Equation (3) were recalibrated using all the measurements performed for the original soil ($BC=0\%$). In this case, the b and c coefficients (i.e., the exponents of the Froude number and slope, respectively) are equal to 1.1241 and 0.891.

For each investigated biochar concentration, the behaviour of the pairs (Re , $\Gamma_v / (F^{1.1241} s^{-0.891})$) was investigated and the values of the coefficients a and e of Equation (3) were estimated by the least-square technique. These coefficients were related to biochar concentration according to the following relationships:

$$a = 0.0303 + 0.0022BC \quad (6)$$

$$e = 0.2492 - 0.0058BC \quad (7)$$

Introducing $b=1.1241$, $c=0.891$ and the a and e coefficients estimated by Equations (6) and (7) into Equation (3),

the corresponding f values were calculated by Equation (1) (Figure 8). The agreement between measured and calculated f values is characterised by errors that are less than $\pm 15\%$ for 77.8% of the examined cases and less than or equal $\pm 10\%$ for 59.2% of the examined cases.

As an alternative approach, the variable biochar concentration was directly included in the model and Equation (3) was modified as follows:

$$\Gamma_v = a \frac{F^b Re^e}{s^c (100 - BC)^d} \quad (8)$$

All the available data were used to calibrate Equation (8), obtaining $a=12525$, $b=1.034$, $c=0.825$, $d=2.648$ and $e=0.166$. Introducing these values into Equation (1), the following flow resistance law is obtained:

$$f = 8 \left[\frac{2^{1-\delta} Re^\delta}{(\delta+1)(\delta+2)} 12,525 \frac{F^{1.034} Re^{0.166}}{s^{0.825} (100 - BC)^{2.648}} \right]^{-2/(1+\delta)} \quad (9)$$

Figure 9 shows the comparison between the measured friction factor values and those calculated by Equation (9). The agreement between the measured and calculated friction factor values is characterised by errors that are always less than $\pm 15\%$ and less than or equal to $\pm 10\%$ for 92.6% of the examined cases.



FIGURE 5 | DEM of difference (DoD) obtained for the rills with a biochar concentration of 0% (rill₀), 3% (rill₃) and 5% (rill₅).

4 | Discussion

4.1 | Rill Erosion in Biochar-Amended Soils

The developed analysis highlighted that, for the investigated slope and discharge, the addition of an initial biochar concentration of 3% can be considered a good soil conservation practice as it reduces soil erosion phenomena. In fact, the results

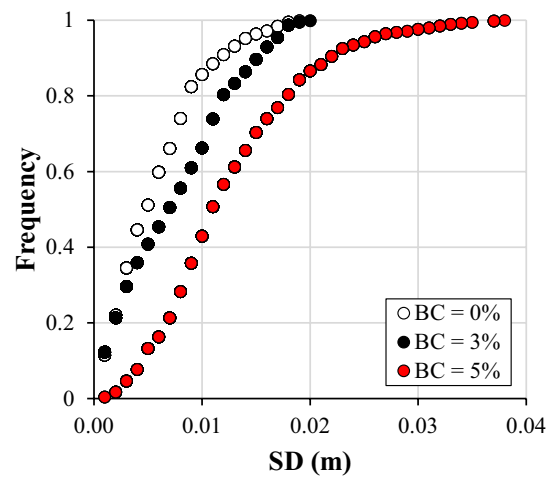


FIGURE 6 | Cumulative frequency distributions of the scour depth values SD for the three experimental conditions.

TABLE 3 | Mean scour depth (SD_{mean}), maximum scour depth (SD_{max}) and standard deviation $\sigma(SD)$ of the three experimental conditions.

BC (%)	SD_{mean} (m)	SD_{max} (m)	$\sigma(SD)$ (m)
0	0.0061	0.0190	0.00416
3	0.0078	0.0200	0.00523
5	0.0128	0.0380	0.00685

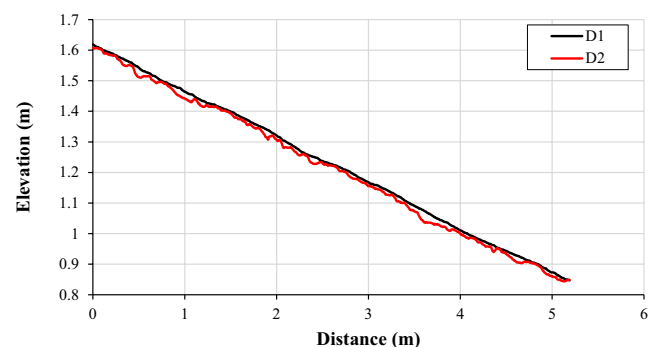


FIGURE 7 | Rill thalweg profiles obtained before (D1) and after the runs (D2) as follows: an example for the rill₅.

showed that rill₃ is characterised by the lowest total eroded volume V_r ($V_3 < V_0$) (Table 2). Moreover, even if the differences between rill₀ and rill₃ in terms of mixture weight W_m (Figure 4a) are negligible, for $BC = 3\%$, a fraction of W_m is due to the biochar weight, thus reducing the sediment component. In other words, the $BC = 3\%$ treatment has a positive effect on soil erosion and favours the preferential transport of the light biochar particles, whose concentration increases to the value $BC_m = 4.1\%$. Instead, the $BC = 5\%$ treatment determined an increase in eroded volume V_r , mixture weight W_m and sediment weight W_s . Furthermore, the BC_m value (3.2%) is lower than the initial concentration of 5%, suggesting that, in this case, preferential biochar particle transport does not occur. The biochar addition and its mixing with soil particles can induce two contrasting results: initially, the cohesionless biochar particles negatively affect the cohesion characteristics of the mixture;

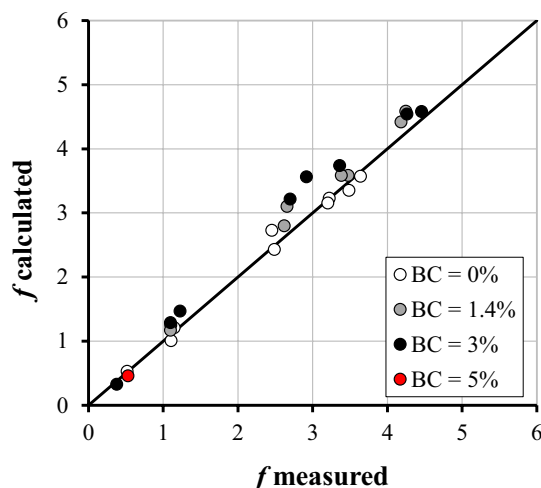


FIGURE 8 | Comparison between the measured friction factor values f and those calculated by introducing Equation (3), with $b=1.1241$, $c=0.891$ and the a and e coefficients estimated by Equations (6) and (7) into Equation (1).

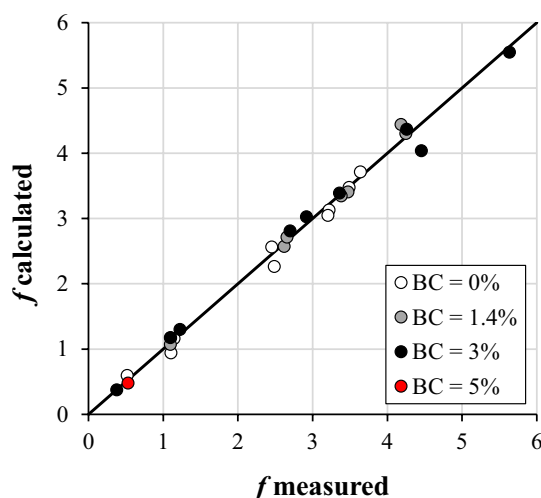


FIGURE 9 | Comparison between the measured friction factor values f and those calculated by Equation (9).

then, the aggregating biochar action, which increases with the incubation period, determines an improvement of soil characteristics and reduces soil particle transportability. If the incubation period is short, the cohesionless effects can prevail on the aggregation one. Thus, the difference in terms of preferential biochar particle transport between $rill_3$ and $rill_5$ can be justified by the circumstance that, in the latter case (5%), the higher biochar component in the mixture decreased the mixture cohesion and determined an increase in soil particle transportability. In other words, for $rill_3$, the biochar initially reduced the mixture cohesion, but the incubation period was long enough to ensure a decrease of soil particle transportability, while for $rill_5$ the positive short-term effects are too weak due to the high biochar content and the mixture remains cohesionless. It is also worth noting that, for $BC=3\%$, the different value of the ratio W_m/V_r (2.66 kg L^{-1}) could indicate an amendment effect, such as increased soil aggregation and modified porosity. In fact, for a fixed eroded volume estimated

by the DoD analysis, the mixture weight of $rill_3$ is higher than those for other treatments. The discrepancy in this ratio could also be partially justified by a possible different degree of compaction when the amended soil was put back into the trenches after the mixing phase or by minimum uncertainties in the volume estimate due to the survey and model generation.

These results agree with those obtained in previous interrill experiments by Li et al. (2019, 2020), who demonstrated that after an incubation period of 8 months, $BC < 3\%$ can limit soil erosion, while higher BC generally favour erosive processes. Li et al. (2021) and Parhizkar et al. (2023) performed investigations on the effects of biochar on rill erosion processes. In particular, Li et al. (2021), for one- and two-years incubation periods, found a decreased susceptibility to rill formation for biochar addition up to $BC=3\%$, while Parhizkar et al. (2023) found that, also for a short incubation period (3 months), biochar addition with $BC=3\%$ reduced rill erodibility. Instead, the obtained results regarding the comparison between the two treatments ($BC=3$ and 5%) do not agree with those by Conte et al. (2025), who stated that $BC=5\%$ was more efficient than $BC=3\%$ in mitigating rill erosion phenomena. However, these discrepancies can be justified by the fact that these authors did not collect all the mixture in the storage tank but only three samples of the outflow discharge. Therefore, the difference can be attributed to a different sampling technique (global vs. partial sampling). Moreover, these discrepancies could also be attributed to different experimental conditions (i.e., incubation period length and lack of bare soil condition) with respect to the work by Conte et al. (2025).

Li et al. (2025) investigated the mid- and long-term effects of wood-biochar addition on rill erodibility K_r and critical shear stress τ_c using samples collected from field plots that had received BC values equal to 0%, 1%, 2.5%, 4%, 5.5% and 7% (w/w) after 1, 2 and 3 years, respectively. After 1–2 years (i.e., mid-term), in comparison with an unamended soil, amended soils with $BC=1\%–4\%$ showed a reduction in K_r and an increase of τ_c . On the contrary, an addition of biochar with $BC=5.5\%–7\%$ increased K_r and decreased τ_c ; that is, increased the rill flow detachment capacity. The results of Li et al. (2025) regarding the BC effect in the mid-term (incubation period of 1–2 years) agree with those of the present investigation, which considers the short-term (1 month) effects of biochar addition with different BC values. Interestingly, Li et al. (2025) concluded that a longer incubation period (3 years) allows, for all the investigated BC values, for obtaining a reduction of K_r and an increase of τ_c in comparison with the control condition.

The comparison between the *mid-* and *long-term* effects of biochar studied by Li et al. (2025) and the *short-term* effects investigated in this paper allows for concluding that, in the long term, a reduction of soil loss is assured for all the applied biochar concentrations, while the short- and mid-term positive effects of biochar addition on soil erosion phenomena are strongly dependent on the applied BC ($\leq 3\%–4\%$). This finding corroborates, in agreement with the results by Li et al. (2025) regarding the improved soil characteristics (cohesion, mean weight diameter of the soil particle aggregates and total organic carbon), the abovementioned hypothesis that biochar needs time to perform its aggregation action that is dependent

on the added concentration. In other words, the more the biochar added, the more the time required to observe an effect on erosion control.

Thus, biochar addition to soil with BC values higher than 3%–4% cannot be considered a good soil conservation practice for short and mid-term, while for long-term applications, the use of biochar as a soil amendment is always (i.e., also for high BC) a useful strategy to limit rill flow detachment capacity. In practical applications, high-erosive rainfall events occurring in the short and mid-term after the biochar application with BC higher than 3% could activate relevant erosion processes. This limit could be overcome by coupling the biochar addition, which enhances water retention and nutrient availability and has positive effects on plant growth and development, with the seeding of a suitable cover crop.

An important limitation of the present study that must be acknowledged is that only a single replicate was performed for each treatment. As a result, the observed differences among treatments should be interpreted with caution. The findings reported herein should therefore be considered preliminary and indicative of potential trends that require confirmation through future studies. Consequently, the conclusions drawn from these results should be regarded as exploratory rather than definitive.

4.2 | Rill Flow Resistance in Biochar-Amended Soils

As abovementioned, the biochar addition with $BC=3\%$ determined a decrease in total flow resistance ($f=0.377$) as compared to the control condition (0.518). Instead, the treatment with $BC=5\%$ gives f value (0.529) comparable with the control condition. These last results could be considered as unexpected as the overall erosion phenomena (in terms of eroded mixture) of the control condition and $rill_3$ are comparable (Figure 4a and Table 2), while those occurring in $rill_5$ are significantly harder. However, the total Darcy–Weisbach friction factor f is the result of the sum among the components due to grain roughness f_g , bed-forms f_b (Pampalone et al. 2021) and sediment transport f_t (accounting for detachment and transport phenomena) (Di Stefano et al. 2022b). The analysis demonstrated that $rill_0$ and $rill_3$ are characterised by comparable mixture weights (Figure 4a). However, the mixture transported in $rill_3$ is made of sediment and biochar and this last is way lighter (i.e., more transportable) than soil aggregates. Therefore, for a comparable transported mixture amount (W_m), the flow moving in $rill_3$ dissipates less energy to transport the mixture. Instead, for the two examined conditions, dissipations due to the detachment phenomena are comparable as biochar determined particle aggregation. In conclusion, for $rill_3$, the f_t component, which considers both detachment and transport phenomena, is less than that for $rill_0$. Considering that the statistics of SD (Table 3) of $rill_0$ and $rill_3$ are comparable, the two conditions are characterised by similar f_b components. Even if biochar addition is expected to increase grain roughness (biochar particle sizes higher than the soil ones), the decrease of the total flow resistance for $rill_3$

demonstrates that the reduction of the transport component f_t prevails over the increased grain component f_g .

Instead, for $rill_5$, the grain roughness is higher as the percentage of particles with higher size increased (due to the presence of biochar particles); flow dissipated a higher quota of its energy due to the bedforms (Figure 7) and transported more mixture particles (Figure 4a) as compared to the $rill_0$ and $rill_3$ conditions. Nevertheless, the expected increase in total flow resistance is partially reduced by the lower dissipation required to detach the cohesionless particles as biochar addition in this concentration (5%) was ineffective for the short term. For these reasons, the total flow resistance of $rill_5$ is comparable with that of $rill_0$, while $rill_3$ determined a reduction in total flow resistance.

Figure 8 highlights that using Equation (3) with $b=1.1241$, $c=0.891$ and a and e coefficients estimated by Equations (6) and (7) yields an estimate of the Darcy–Weisbach friction factor less accurate than that obtained by Equation (9) (Figure 9). In particular, the proposed flow resistance equation (Equation 9) allows an estimate of the Darcy–Weisbach friction factor characterised by errors less than or equal to $\pm 10\%$ for 92.6% of the examined cases. The less accurate f estimates by an approach (Equation 3) similar to that applied by Nicosia, Pampalone, and Ferro (2021) for the measurements by Li et al. (2021) can be explained by the fact that these measurements (Li et al. 2021) were obtained for simulated rainfall experiments, while, in this study, a constant inflow discharge was entered upstream of the rill. This experimental difference also determined that the flows in the study by Li et al. (2021) were always subcritical, while those of this study are always supercritical. Moreover, as compared to the flow resistance law proposed by Nicosia, Pampalone, and Ferro (2021), Equation (9) can be applied for a wider range of experimental conditions. In detail, it is applicable for slopes varying from 3.1% to 15.1%, BC varying from 0% to 5%, both subcritical and supercritical flows and laminar, transitional and turbulent flow regimes.

Since $Re^\delta=4.4817$, Equation (9) can be rewritten as follows:

$$f = 8 \left[\frac{(\delta+1)(\delta+2)}{4.48172^{1-\delta} 12525} \right]^{2/(1+\delta)} \left[\frac{s^{0.825} (100-BC)^{2.648}}{F^{1.034} Re^{0.166}} \right]^{2/(1+\delta)} \quad (10)$$

As δ can be assumed equal to the mean experimental value of 0.2, Equation (10) demonstrates that, for given hydraulic conditions (F , Re and s), the Darcy–Weisbach friction factor decreases when the biochar concentration BC (%) increases. For fixed hydraulic conditions, this last result allows for concluding that biochar can reduce rill flow resistance. This conclusion agrees with the hypothesis of Li et al. (2021) that the increase of biochar content damps flow turbulence and, consequently, reduces flow resistance.

Anyway, further investigations are required to assess the theoretical flow resistance equation (Equation (1) coupled with Equation (8)) using more measurements performed for hydraulic conditions characterised by a wider range of Froude and Reynolds numbers.

5 | Conclusions

Several research findings evidence that biochar application can be a considerable promise for sustainable erosion control. Although there is an increasing scientific interest in biochar as a soil amendment and a tool to mitigate soil erosion, contrasting results on its significant usefulness as a soil conservation measure were reported in the literature. Furthermore, most of the existing experimental investigations were developed for interrill soil erosion conditions without paying particular attention to the concentration of biochar added to the original soils.

In this paper, the short-term effects on soil amended with biochar in terms of effectiveness in erosion control and rill flow resistance were evaluated by plot scale measurements performed with soil amended with an initial biochar concentration in weight of 3% and 5%. The measurements demonstrated that, in the short term, the addition of $BC=3\%$ is effective in reducing soil erosion phenomena as compared to the control condition, while adding $BC=5\%$ determined an increase in eroded volume. A result that can be deduced by the findings of this study, in agreement with those available in literature, is that biochar requires an incubation period, which is dependent on the added concentration, to perform its aggregation action and reduce soil erosion phenomena. Finally, the analysis demonstrated that the proposed flow resistance equation gives a good estimate of the Darcy–Weisbach friction factor and the flow resistance, for fixed hydraulic conditions, decreases with increasing biochar concentration. In conclusion, for the short term, biochar addition to soil with BC values higher than the 3%–4% cannot be considered a good soil conservation practice.

The main limit of this investigation is the lack of run replicates due to the difficulties in obtaining comparable replicates of the same treatment, which are predominantly related to the flow-shaping action. For this reason, the results of this investigation are relevant with reference to comparison among different treatments (i.e., different biochar concentrations) and need to be validated to have wider applicability.

Anyway, other experimental measurements are needed to determine what happens using other BC values between 3% and 5% and assess if, in the same experimental conditions, these biochar concentrations determine better results in terms of soil loss and flow resistance for longer incubation periods. These new measurements could also be used to test the applicability of the proposed flow resistance equation widening the range of the studied hydraulic conditions. Moreover, further experiments could be performed testing the effect of the same wood biochar, for the same experimental conditions, on a different soil, for which the interacting mechanisms with biochar could be significantly different. If the effectiveness of this wood-biochar is the same, regardless of the investigated soil texture, another biochar (wood-biochar with different physical properties, such as porosity or bulk density, or a different biochar type obtained by the pyrolysis of other substances) could be tested. Furthermore, for the same investigated biochar type and soil texture, the effect of different experimental conditions (slope gradients and flow discharges) should be studied. Finally, the results of this study, obtained for the plot scale, should be assessed at the hillslope scale.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The raw data required to reproduce the above findings are available in the Mendeley repository with the following reference: Nicosia, Alessio; Di Stefano, Costanza; Guida, Gaetano; Lucchese, Antonino; Palmeri, Vincenzo; Pampalone, Vincenzo; Ferro, Vito (2025), “Short-term effects on rill erosion and flow resistance for a wood-biochar amended soil”, Mendeley Data, V1, doi:[10.17632/7vjzxdxrg.1](https://doi.org/10.17632/7vjzxdxrg.1).

References

- Abrol, V., M. Ben-Hur, F. G. A. Verheijen, et al. 2016. “Biochar Effects on Soil Water Infiltration and Erosion Under Seal Formation Conditions: Rainfall Simulation Experiment.” *Journal of Soils and Sediments* 16: 2709–2719. <https://doi.org/10.1007/s11368-016-1448-8>.
- Ahmadi, S. H., H. Ghasemi, and A. R. Sepaskhah. 2020. “Rice Husk Biochar Influences Runoff Features, Soil Loss, and Hydrological Behavior of a Loamy Soil in a Series of Successive Simulated Rainfall Events.” *Catena* 192: 104587. <https://doi.org/10.1016/j.catena.2020.104587>.
- Atkinson, C. J., J. D. Fitzgerald, and N. A. Hipps. 2010. “Potential Mechanisms for Achieving Agricultural Benefits From Biochar Application to Temperate Soils: A Review.” *Plant and Soil* 337: 1–18. <https://doi.org/10.1007/s11104-010-0464-5>.
- Autovino, D., V. Bagarello, C. Bondi, G. Russo, F. Zanna, and K. Zhioua. 2026. “Hydrodynamic Behavior of a Near-Saturated Sandy-Loam Soil Shortly After Incorporating Compost or Zeolite.” *Soil and Tillage Research* 258: 107035. <https://doi.org/10.1016/j.still.2025.107035>.
- Bagarello, V., P. Conte, V. Ferro, et al. 2025. “How Rilling and Biochar Addition Affect Hydraulic Properties of a Clay-Loam Soil.” *European Journal of Soil Science* 76, no. 1: e70034. <https://doi.org/10.1111/ejss.70034>.
- Bagarello, V., G. V. Di Piazza, V. Ferro, and G. Giordano. 2008. “Predicting Unit Plot Soil Loss in Sicily, South Italy.” *Hydrological Processes* 22: 586–595. <https://doi.org/10.1002/hyp.6621>.
- Bagarello, V., C. Di Stefano, V. Ferro, and V. Pampalone. 2015. “Establishing a Soil Loss Threshold for Limiting Rilling.” *Journal of Hydrologic Engineering* 20: C6014001. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001056](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001056).

- Bagarello, V., and V. Ferro. 2010. "Analysis of Soil Loss Data From Plots of Different Length for the Sparacia Experimental Area, Sicily, Italy." *Biosystems Engineering* 105: 411–422. <https://doi.org/10.1016/j.biosystemseng.2009.12.015>.
- Bagarello, V., V. Ferro, and D. C. Flanagan. 2018. "Predicting Plot Soil Loss by Empirical and Process-Oriented Approaches. A Review." *Journal of Agricultural Engineering* XLIX, no. 710: 1–18. <https://doi.org/10.4081/jae.2018.710>.
- Bagarello, V., V. Ferro, G. Giordano, et al. 2011. "Effect of Plot Size on Measured Soil Loss for Two Italian Experimental Sites." *Biosystems Engineering* 108: 18–27. <https://doi.org/10.1016/j.biosystemseng.2010.10.006>.
- Barenblatt, G. I. 1991. "On the Scaling Laws (Incomplete Self-Similarity With Respect to Reynolds Numbers) for the Developed Turbulent Flows in Tubes." *Comptes Rendus de L'Académie des Sciences. Série II, Mécanique, Physique, Chimie, Sciences de la Terre et de L'univers* 313: 307–312.
- Blanco-Canqui, H. 2017. "Biochar and Soil Physical Properties." *Soil Science Society of America Journal* 81: 687–711. <https://doi.org/10.2136/sssaj2017.01.0017>.
- Borrelli, P., D. A. Robinson, L. R. Fleischer, et al. 2017. "An Assessment of the Global Impact of 21st Century Land Use Change on Soil Erosion." *Nature Communications* 8, no. 1: 2013. <https://doi.org/10.1038/s41467-017-02142-7>.
- Bruno, C., C. Di Stefano, and V. Ferro. 2008. "Field Investigation on Rilling in the Experimental Sparacia Area, South Italy." *Earth Surface Processes and Landforms* 33: 263–279. <https://doi.org/10.1002/esp.1544>.
- Busscher, W. J., J. M. Novak, D. E. Evans, D. W. Watts, M. A. S. Niandou, and M. Ahmedna. 2010. "Influence of Pecan Biochar on Physical Properties of a Norfolk Loamy Sand." *Soil Science* 175: 10–14. <https://doi.org/10.1097/SS.0b013e3181cb7f46>.
- Carollo, F. G., C. Di Stefano, A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2021. "Flow Resistance in Mobile Bed Rills Shaped in Soils With Different Texture." *European Journal of Soil Science* 72, no. 5: 2062–2075. <https://doi.org/10.1111/ejss.13093>.
- Carollo, F. G., C. Di Stefano, A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2023. "A New Strategy to Assure Compliance With Soil Loss Tolerance at a Regional Scale." *Catena* 223: 106945.
- Castaing, B., Y. Gagne, and E. J. Hopfinger. 1990. "Velocity Probability Density Functions of High Reynolds Number Turbulence." *Physica D* 46: 177–200. [https://doi.org/10.1016/0167-2789\(90\)90035-N](https://doi.org/10.1016/0167-2789(90)90035-N).
- Castellini, M., L. Giglio, M. Niedda, A. D. Palumbo, and D. Ventrella. 2015. "Impact of Biochar Addition on the Physical and Hydraulic Properties of a Clay Soil." *Soil and Tillage Research* 154: 1–13. <https://doi.org/10.1016/j.still.2015.06.016>.
- Conte, P., C. Librici, A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2025. "Wood-Biochar Influence on Rill Erosion Processes and Hydrological Connectivity in Amended Soils." *Hydrological Processes* 39, no. 2: e70093. <https://doi.org/10.1002/hyp.70093>.
- Di Stefano, C., V. Ferro, and V. Pampalone. 2015. "Modeling Rill Erosion at the Sparacia Experimental Area." *Journal of Hydrologic Engineering* 20: C5014001. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001057](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001057).
- Di Stefano, C., V. Ferro, and V. Pampalone. 2016. "Measuring Field Rill Erodibility by a Simplified Method." *Land Degradation and Development* 27: 239–247. <https://doi.org/10.1002/ldr.2411>.
- Di Stefano, C., V. Ferro, V. Pampalone, and F. Sanzone. 2013. "Field Investigation of Rill and Ephemeral Gully Erosion in the Sparacia Experimental Area, South Italy." *Catena* 101: 226–234. <https://doi.org/10.1016/j.catena.2012.10.012>.
- Di Stefano, C., A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2020. "Dye-Tracer Technique for Rill Flows by Velocity Profile Measurements." *Catena* 185: 104313. <https://doi.org/10.1016/j.catena.2019.104313>.
- Di Stefano, C., A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2021. "Flume Experiments for Assessing the Dye-Tracing Technique in Rill Flows." *Flow Measurement and Instrumentation* 77: 101870. <https://doi.org/10.1016/j.flowmeasinst.2020.101870>.
- Di Stefano, C., A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2022a. "Rill Flow Velocity and Resistance Law: A Review." *Earth Science Reviews* 231: 104092. <https://doi.org/10.1016/j.earscirev.2022.104092>.
- Di Stefano, C., A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro. 2022b. "Rill Flow Resistance Law Under Sediment Transport." *Journal of Soils and Sediments* 22: 334–347. <https://doi.org/10.1007/s11368-021-03083-x>.
- Di Stefano, C., A. Nicosia, V. Pampalone, and V. Ferro. 2023. "Soil Loss Tolerance in the Context of the European Green Deal." *Heliyon* 9, no. 1: e12869. <https://doi.org/10.1016/j.heliyon.2023.e12869>.
- Di Stefano, C., A. Nicosia, V. Pampalone, V. Palmeri, and V. Ferro. 2019. "New Technique for Measuring Water Depth in Rill Channels." *Catena* 181: 104090. <https://doi.org/10.1016/j.catena.2019.104090>.
- Doan, T. T., T. Henry-Des-Tureaux, C. Rumpel, J. L. Janeau, and P. Jouquet. 2015. "Impact of Compost, Vermicompost and Biochar on Soil Fertility, Maize Yield and Soil Erosion in Northern Vietnam: A Three Year Mesocosm Experiment." *Science of the Total Environment* 514: 147–154. <https://doi.org/10.1016/j.scitotenv.2015.02.005>.
- Gholamamjadi, B., S. Jeffery, O. Gonzales-Pelayo, et al. 2023. "Biochar Impacts on Runoff and Soil Erosion by Water: A Systematic Global Scale Meta-Analysis." *Science of the Total Environment* 871: 161860. <https://doi.org/10.1016/j.scitotenv.2023.161860>.
- Govers, G., R. Giménez, and K. Van Oost. 2007. "Rill Erosion: Exploring the Relationship Between Experiments, Modeling and Field Observations." *Earth-Science Reviews* 84: 87–102. <https://doi.org/10.1016/j.earscirev.2007.06.001>.
- Guerra, B., and K. Steenwerth. 2012. "Influence of Floor Management Technique on Grapevine Growth, Disease Pressure, and Juice and Wine Composition: A Review." *American Journal of Enology and Viticulture* 63, no. 2: 149–164. <https://doi.org/10.5344/ajev.2011.10001>.
- Herath, H., M. Camps-Arbestain, and M. Hedley. 2013. "Effect of Biochar on Soil Physical Properties in Two Contrasting Soils: An Alfisol and an Andisol." *Geoderma* 209: 188–197. <https://doi.org/10.1016/j.geoderma.2013.06.016>.
- Hseu, Z., S. H. Jien, W. H. Chien, and R. C. Liou. 2014. "Impacts of Biochar on Physical Properties and Erosion Potential of a Mudstone Slope Soil." *Scientific World Journal* 2014: 602197. <https://doi.org/10.1155/2014/602197>.
- Jiang, Z., S. Huang, and Z. Meng. 2025. "Long-Term Effects of Biochar on the Hydraulic Properties of Soil: A Meta-Analysis Based on 1–10 Years Field Experiments." *Geoderma* 458: 117318. <https://doi.org/10.1016/j.geoderma.2025.117318>.
- Jien, S. H., and C. S. Wang. 2013. "Effects of Biochar on Soil Properties and Erosion Potential in a Highly Weathered Soil." *Catena* 110: 225–233. <https://doi.org/10.1016/j.catena.2013.06.021>.
- Joseph, S. D., M. Camps-Arbestain, Y. Lin, et al. 2010. "An Investigation Into the Reactions of Biochar in Soil." *Soil Research* 48, no. 7: 501–515. <https://doi.org/10.1071/SR10009>.
- Köppen, W. 1918. "Classification of Climates According to Temperature, Precipitation and Seasonal Cycle." *Petermanns Geographische Mitteilungen* 64: 193–203.
- Kroetsch, D., and C. Wang. 2008. "Chapter 55 Particle Size Distribution." In *Soil Sampling and Methods of Analysis*, edited by M. R. Carter and E. G. Gregorich, 2nd ed., 713–725. Taylor & Francis Group.

- Lee, C. H., C. C. Wang, H. H. Lin, et al. 2018. "In-Situ Biochar Application Conserves Nutrients While Simultaneously Mitigating Runoff and Erosion of an Fe-Oxide-Enriched Tropical Soil." *Science of the Total Environment* 619–620: 665–671. <https://doi.org/10.1016/j.scitotenv.2017.11.023>.
- Lee, S. S., H. S. Shah, Y. M. Awad, et al. 2015. "Synergy Effects of Biochar and Polyacrylamide on Plant Growth and Soil Erosion Control." *Environmental Earth Sciences* 74: 2463–2473. <https://doi.org/10.1007/s12665-015-4262-5>.
- Li, Q. X., Z. W. Jin, X. M. Chen, Y. Jing, Q. R. Huang, and J. B. Zhang. 2017. "Effects of Biochar on Aggregate Characteristics of Upland Red Soil in Subtropical China." *Environmental Earth Sciences* 76: 372. <https://doi.org/10.1007/s12665-017-6703-9>.
- Li, T., P. Yu, D. Liu, et al. 2021. "Effects of Biochar on Sediment Transport and Rill Erosion After Two Consecutive Years of Seasonal Freezing and Thawing." *Sustainability* 13: 6984. <https://doi.org/10.3390/su13136984>.
- Li, Y., G. Feng, H. Tewolde, M. Yang, and F. Zhang. 2020. "Soil, Biochar, and Nitrogen Loss to Runoff From Loess Soil Amended With Biochar Under Simulated Rainfall." *Journal of Hydrology* 591: 125318. <https://doi.org/10.1016/j.jhydrol.2020.125318>.
- Li, Y., Y. Yuan, J. Zhao, et al. 2025. "Biochar Addition Enhances Silt Loam Resistance to Rill Flow: A Study Based on Three Years of Field Monitoring Data on China's Loess Plateau." *Soil & Tillage Research* 245: 106320. <https://doi.org/10.1016/j.still.2024.106320>.
- Li, Y. Y., F. B. Zhang, M. Y. Yang, J. Q. Zhang, and Y. G. Xie. 2019. "Impacts of Biochar Application Rates and Particle Sizes on Runoff and Soil Loss in Small Cultivated Loess Plots Under Simulated Rainfall." *Science of the Total Environment* 649: 1403–1413. <https://doi.org/10.1016/j.scitotenv.2018.08.415>.
- Mutchler, C. K., and R. A. Young. 1975. "Soil Detachment by Raindrops." In *Present and Prospective Technology for Predicting Sediment Yields and Sources*, 113–117. USDA Sedimentation Laboratory.
- Nicosia, A., C. Di Stefano, V. Palmeri, V. Pampalona, and V. Ferro. 2021. "Roughness Effect on the Correction Factor of Surface Velocity for Rill Flows." *Hydrological Processes* 35, no. 10: e14407. <https://doi.org/10.1002/hyp.14407>.
- Nicosia, A., V. Pampalona, and V. Ferro. 2021. "Effects of Biochar Addition on Rill Flow Resistance." *Water* 13: 3036. <https://doi.org/10.3390/w13213036>.
- Novara, A., A. Cerda, E. Barone, and L. Gristina. 2021. "Cover Crop Management and Water Conservation in Vineyard and Olive Orchards." *Soil and Tillage Research* 208: 104896. <https://doi.org/10.1016/j.still.2020.104896>.
- Ogle, S. M. 2019. "The Intergovernmental Panel on Climate Change (IPCC)." In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, edited by E. Calvo Buendia, K. Tanabe, A. Kranjc, et al., vol. IV. Intergovernmental Panel on Climate Change.
- Pampalona, V., C. Di Stefano, A. Nicosia, V. Palmeri, and V. Ferro. 2021. "Analysis of Rill Step-Pool Morphology and Its Comparison With Stream Case." *Earth Surface Processes and Landforms* 46, no. 4: 775–790. <https://doi.org/10.1002/esp.5063>.
- Parhizkar, M., M. Shabanpour, M. E. Lucas-Borja, and D. A. Zema. 2023. "Effects of Rice Husk Biochar on Rill Detachment Capacity in Deforested Hillslopes." *Ecological Engineering* 191: 106964. <https://doi.org/10.1016/j.ecoleng.2023.106964>.
- Peng, W., Z. Zhang, and K. Zhang. 2015. "Hydrodynamic Characteristics of Rill Flow on Steep Slopes." *Hydrological Processes* 29: 3677–3686. <https://doi.org/10.1002/hyp.10461>.
- Peng, X., Q. H. Zhu, Z. B. Xie, F. Darboux, and N. M. Holden. 2016. "The Impact of Manure, Straw and Biochar Amendments on Aggregation and Erosion in a Hillslope Ultisol." *Catena* 138: 30–37. <https://doi.org/10.1016/j.catena.2015.11.008>.
- Quinton, J. N., and P. Fiener. 2024. "Soil Erosion on Arable Land: An Unresolved Global Environmental Threat." *Progress in Physical Geography: Earth and Environment* 48, no. 1: 136–161. <https://doi.org/10.1177/03091333231216595>.
- Sadeghi, S. H. R., Z. Hazbavi, and M. K. Harchegani. 2016. "Controllability of Runoff and Soil Loss From Small Plots Treated by Vinasse-Produced Biochar." *Science of the Total Environment* 541: 483–490. <https://doi.org/10.1016/j.scitotenv.2015.09.068>.
- Schmidt, H. P., C. Kammann, C. Niggli, M. W. Evangelou, K. A. Mackie, and S. Abiven. 2014. "Biochar and Biochar-Compost as Soil Amendments to a Vineyard Soil: Influences on Plant Growth, Nutrient Uptake, Plant Health and Grape Quality." *Agriculture, Ecosystems & Environment* 191: 117–123. <https://doi.org/10.1016/j.agee.2014.04.001>.
- Sharma, P. 2024. "Biochar Application for Sustainable Soil Erosion Control: A Review of Current Research and Future Perspectives." *Frontiers in Environmental Science* 12: 1373287. <https://doi.org/10.3389/fenvs.2024.1373287>.
- Smetanová, A., M. Dotterweich, D. Diehl, U. Ulrich, and N. Fohrer. 2013. "Influence of Biochar and Terra Preta Substrates on Wettability and Erodibility of Soils." *Zeitschrift für Geomorphologie* 57: 111–134. <https://doi.org/10.1127/0372-8854/2012/S-00117>.
- Sohi, S. P., E. Krull, E. Lopezcapel, and R. Bol. 2010. "A Review of Biochar and Its Use and Function in Soil." *Advances in Agronomy* 105: 47–82. [https://doi.org/10.1016/S0065-2113\(10\)05002-9](https://doi.org/10.1016/S0065-2113(10)05002-9).
- Telles, T. S., T. R. D. Melo, A. J. Righetto, E. J. Didoné, and G. M. D. C. Barbosa. 2022. "Soil Management Practices Adopted by Farmers and How They Perceive Conservation Agriculture." *Revista Brasileira de Ciência do Solo* 46: e0210151.
- Thomsen, T. 2024. *Short Survey: Political Regulation of Biochar Production and Use in Agricultural Soils*, 27. Roskilde Universitet.
- Wang, J., and S. Wang. 2019. "Preparation, Modification and Environmental Application of Biochar: A Review." *Journal of Cleaner Production* 227: 1002–1022. <https://doi.org/10.1016/j.jclepro.2019.04.282>.
- Wang, L., Y. S. Ok, D. C. W. Tsang, et al. 2020. "New Trends in Biochar Pyrolysis and Modification Strategies: Feedstock, Pyrolysis Conditions, Sustainability Concerns and Implications for Soil Amendment." *Soil Use and Management* 36, no. 3: 358–386. <https://doi.org/10.1111/sum.12592>.
- Wani, O. A., F. Akhter, S. S. Kumar, et al. 2023. "Mitigating Soil Erosion Through Biomass-Derived Biochar: Exploring the Influence of Feedstock Types and Pyrolysis Temperature." *Land* 12, no. 12: 2111. <https://doi.org/10.3390/land12122111>.
- Woolf, D., J. Lehmann, S. Ogle, A. W. Kishimoto-Mo, B. McConkey, and J. Baldock. 2021. "Greenhouse Gas Inventory Model for Biochar Additions to Soil." *Environmental Science & Technology* 55, no. 21: 14795–14805.
- Zhang, F., C. Huang, M. Yang, J. Zhang, and W. Shi. 2019. "Rainfall Simulation Experiments Indicate That Biochar Addition Enhances Erosion of Loess-Derived Soils." *Land Degradation and Development* 30: 2272–2286. <https://doi.org/10.1002/ldr.3399>.
- Zhang, G. H., R. T. Luo, Y. Cao, R. C. Shen, and X. C. Zhang. 2010. "Correction Factor to Dye-Measured Flow Velocity Under Varying Water and Sediment Discharges." *Journal of Hydrology* 389, no. 1–2: 205–213. <https://doi.org/10.1016/j.jhydrol.2010.05.050>.
- Zhang, P., H. Tang, W. Yao, N. Zhang, and L. V. Xizhi. 2016. "Experimental Investigation of Morphological Characteristics of Rill Evolution on Loess Slope." *Catena* 137: 536–544. <https://doi.org/10.1016/j.catena.2015.10.025>.