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How Do Newly-Amended Biochar Particles Affect Erodibility and Soil Water Movement?—A Small-Scale Experimental Approach

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Abstract: Biochar amendment changes chemical and physical properties of soils and influences soil biota. It is, thus, assumed that it can also affect soil erosion and erosion-related processes. In this study, we investigated how biochar particles instantly change erodibility by rain splash and the initial movement of soil water in a small-scale experiment. Hydrothermal carbonization (HTC)-char and Pyrochar were admixed to two soil substrates. Soil erodibility was determined with Tübingen splash cups under simulated rainfall, soil hydraulic conductivity was calculated from texture and bulk soil density, and soil water retention was measured using the negative and the excess pressure methods. Results showed that the addition of biochar significantly reduced initial soil erosion in coarse sand and silt loam immediately after biochar application. Furthermore, biochar particles were not preferentially removed from the substrate surface, but increasing biochar particle sizes partly showed decreasing erodibility of substrates. Moreover, biochar amendment led to improved hydraulic conductivity and soil water retention, regarding soil erosion control. In conclusion, this study provided evidence that biochar amendments reduce soil degradation by water erosion. Furthermore, this effect is detectable in a very early stage, and without long-term incorporation of biochar into soils.

Keywords: biochar; soil erosion; splash erosion; soil water characteristics; splash cup experiment

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1. Introduction

Biochar is charcoal obtained by thermal decomposition of biomass through pyrolysis [1,2]. Similar to black carbon derived from the incomplete combustion of vegetation during wild fires, the carbon-enriched solid matter is known to improve, for example, cation exchange capacity or base saturation, as soils of the Amazon Basin indicate ("Terra Preta do Indio"; [3,4]). Thus, biochar was introduced to other environments as a soil amendment. Its addition to topsoils can lead to significant changes in soil characteristics [1]. Additionally, its persistence in topsoils lasts longer than any other form of organic matter that is commonly used in agriculture. Therefore, associated benefits regarding soil fertility arise [5–7]. Nevertheless, its impact on soil functions is a controversial subject [8]. The effect of biochar generally relies on specific influences on the equilibrium between release (e.g., desorption) and fixation (e.g., adsorption) mechanisms in substrates [1,9]. Its application to soil adds to the natural soil C stocks and offers an enormous reaction surface for soil chemical and soil biological processes [10–12]. Furthermore, physical effects between soil and biochar are reported (e.g., [13,14]), which can also affect soil texture and, thus, erodibility of substrates, and the transport and storage of water within them [15–20].

First field experiments confirm erosion-reducing effects of biochar after several years of application, due to increased organic matter content inducing higher aggregate stability and increased saturated conductivity [21,22]. In addition to this well-conceivable, positive long-term effect of biochar application, a short-term effect is assumed, since the biochar particles change the overall soil texture and bulk soil density [23,24]. Most likely, silting and soil detachment by splash erosion is reduced by coarser particles on the soil surface [25], and biochar particles of different size interact with raindrops of different size. There is general evidence that larger amounts of newly amended biochar particles can be transported on agricultural land by interrill erosion, if heavy rainstorms occur (e.g., [26,27]). Rumpel et al. [28–30] showed, in a series of studies, that biochar tends to be preferentially eroded down-slopes, and highlighted the importance to investigate splash erosion effects. Guggenberger et al. [31] found that a larger fraction of biochar was eroded compared to other soil organic matter fractions in permafrost soils. This implies that larger pieces of biochar are more likely to be transported by preferential erosion. In this context, the application strategy plays a crucial role, as only active incorporation of biochar into the soil prevents the risk of particles being directly transported by wind and water [8]. Considering splash erosion, the amended biochar will absorb the kinetic energy without being detached, if the raindrop is smaller in diameter than the biochar [32,33]. Thus, we assume an effect of biochar on soil substrate erodibility induced by rain splash. However, most studies focus on erosion and transport of biochar particles on the surface, but do not consider the erodibility of the given substrate or soil amended with biochar itself. Also, specific investigations of the splash process without confounding factors, such as sheet or rill erosion, have not yet taken place.

Biochar amendment can further affect initial soil erosion processes by altering soil water relations [34], as, for example, an increase in hydraulic conductivity can lead to reduced surface runoff, which can in turn be influenced by soil water retention [35,36]. Soil surface properties, such as texture, soil structure, and related drainage properties, importantly affect infiltration excess and overland flow [35]. We assume that specific biochar particles can play a role in increasing infiltration rates. However, biochar particles with different properties might also lead to reduced infiltration rates when, for example, fine biochar particles fill in small pore spaces in topsoils or increase hydrophobicity [8,37]. In this regard, experiments have shown that soil water retention in sandy soils was improved when biochar or charcoal was amended [18,38]. Ajayi et al. [16] indicated that biochar amendment alters the pore structure, leading to an increase of saturated hydraulic conductivity in a sandy loam substrate. The same authors found that the amendment of fine sand with woodchip-biochar improved the water retention capacity and interparticle bonding of the substrate, depending on the rate of amendment and water content of the substrates [39]. In pot experiments, it could be shown that biochar amendment improved the soil structure of coarse-textured soils, depending on the type of biochar used. Biochar from straw increased the available water capacity, but biochar made from woodchips had no effect [18]. Another study used two different biochar types with different application rates, and found that biochar amendment generally increased the available water capacity in a loamy sand, but to varying degrees [40].

The specific impacts on both erodibility and soil water movement vary with the type of biochar used, for example produced from different raw material or under different pyrolysis conditions [41–43]. As an example, research on the properties of biochar showed that the microporosity and wettability of different types of biochar is increased through high inert gas flow rates during production [44]. In this context, Verheijen [8] states that biochar properties reported in literature are highly heterogeneous, which makes the identification of underlying mechanisms rather difficult. At the same time, it provides an opportunity to create specific biochars with properties that are best suited to a particular site or task such as erosion control.

In conclusion, it is likely that while biochar influences soil chemical and physical processes as well as soil biota, it also affects soil erosion [2,21]. We assume that this effect is already valid shortly after the addition of biochar to soils. As the effects of biochar on soil losses and on the transport of adjunct inorganic soil particles are not well understood, further experimental monitoring appears to be necessary (cf. [45]). This is particularly true regarding specific small-scale mechanisms behind these effects, such as splash erosion or initial water movement in substrates [8,46]. We assume that the particle size and amount of biochar amendment, as well as its type, have a direct effect on soil erodibility and erosion-influencing soil water movements. Thus, biochar affects water erosion immediately after incorporation. A laboratory experiment was conducted under controlled conditions on how different types and quantities of admixed biochar particles affect a sandy and a silty loam substrate. Soil erodibility was determined with Tübingen splash cups as rain splash under simulated rainfall. To characterize soil water movements, soil hydraulic conductivity was calculated, and soil water retention was measured as water holding capacity using the negative pressure, as well as the excess pressure, method. We addressed the hypotheses that the addition and active incorporation of biochar:

1. decreases the erodibility of sandy and silty soil substrates by splash erosion,

and

2. leads to increased hydraulic conductivity and soil water retention directly after amendment.

2. Materials and Methods

Two biochar types made from green waste were used for the experiment (cf. [47]). Pyrochar (Pyrolysis char, Ithaka Institut, Arbaz, Switzerland) was generated through pyrolysis at 700 °C with a density of 2.01 g cm^{-3}. Hydrothermal carbonization (HTC)-char (Addlogic Labs GmbH, Jettingen, Germany) was produced through hydrothermal carbonization at 200 °C with a density of 1.60 g cm^{-3}. Both biochars were dried before the experiment at 40 °C, and sieved to particle sizes of 2–5 mm, 1–2 mm, and <1 mm. As experimental substrates, a coarse sand (97.9% sand, 0.3% silt, 1.75% clay) was used from the Steidle sandpit close to Sigmaringen, Germany. Furthermore, a sieved silt loam (3.2% sand, 71.6% silt, 25.3% clay) was obtained from a loamy substrate originally collected on the Swabian Alb, Germany. Biochar was added with 2, 6, and 10 weight percentages to the substrates, corresponding to an application rate of 10.4 Mg ha^{-1}, 31.2 Mg ha^{-1}, or 52.0 Mg ha^{-1}, respectively. The soil was artificially mixed in the laboratory after adding the respective biochar components to the substrate and using an electromechanical stirring device. Time for stirring was 1 min for each sample to guarantee adequate mixing of the artificial substrates. Additionally, two treatments of coarse sand and silt loam without biochar amendment were used as control. Thus, 38 treatments were realized in the experimental design (Table 1).

Table 1. Substrates, biochar types, application rates, and particle sizes used within the experimental setup.

Substrate	Biochar Type and Application Rate	Biochar Particle Size
Coarse sand (97.9% sand, 0.3% silt, 1.75% clay)	2% Pyrochar	<1 mm, 1–2 mm or 2–5 mm
	6% Pyrochar	<1 mm, 1–2 mm or 2–5 mm
	10% Pyrochar	<1 mm, 1–2 mm or 2–5 mm
	2% HTC-char	<1 mm, 1–2 mm or 2–5 mm
	6% HTC-char	<1 mm, 1–2 mm or 2–5 mm
	10% HTC-char	<1 mm, 1–2 mm or 2–5 mm
	Control, no addition	
Silt loam (3.2% sand, 71.6% silt, 25.3% clay)	2% Pyrochar	<1 mm, 1–2 mm or 2–5 mm
	6% Pyrochar	<1 mm, 1–2 mm or 2–5 mm
	10% Pyrochar	<1 mm, 1–2 mm or 2–5 mm
	2% HTC-char	<1 mm, 1–2 mm or 2–5 mm
	6% HTC-char	<1 mm, 1–2 mm or 2–5 mm
	10% HTC-char	<1 mm, 1–2 mm or 2–5 mm
	Control, no addition	

Soil erodibility was measured with modified Tübingen splash cups ("T-cups", cf. [48,49]). Treatments were six-fold replicated, leading to 228 measurements in total (38 × 6 = 228). The prepared substrates were again carefully mixed and homogenized before being filled into T-cups (diameter 5 cm, depth 3.5 cm) by hand, compacted by light tapping and then refilled to the rim. Subsequently, rainfall simulations were conducted using the Tübingen rainfall simulator with its protective wind shield [50,51]. The single-nozzle simulator was set to a drop falling height of 3.8 m with a pressure of 150 hPa at the nozzle (Lechler 460.788.30, Dettingen, Germany). The rainfall spectrum and intensity was calibrated and controlled at every cup position with a laser precipitation monitor (Thies GmbH, Göttingen, Germany; cf. [52]) before the experiment and after the experiment, and adjusted to constant patterns for all measurements. For every measurement, rainfall was applied for 15 min with an intensity of 52 mm h^{-1} and a mean kinetic energy of 5.1 J m^2 mm^{-1}. Splash cups were moistened before measurements and randomly distributed in a hexagonal radial design under the rainfall simulator to ensure homogenous rainfall conditions (Figure 1).

Figure 1. Splash cups with biochar treatments in hexagonal radial design under the Tübingen rainfall simulator.

Soil hydraulic conductivity was calculated using the Soil-Plant-Air-Water (SPAW) modeler (USDA Agricultural Research Service, Beltsville, MD, USA), which is based on a calibration with an extensive data set of soil water characteristics [53]. Effects of different biochar types and sizes could not be directly included in the model, but were reflected by different bulk soil density.

The soil water retention was measured using the negative pressure method for low pressure stages (−1 kPa and −6 kPa) and the excess pressure method for high pressure stages (−30 kPa and −1.5 MPa) with pressure chambers (Eijkelkamp Soil & Water, Giesbeek, The Netherlands) [54]. Treatments were replicated three times (except for treatments requiring Pyrochar sieved to the size of 1–2 mm, which was limited), leading to 108 measurements in total ($38 \times 3 - 6 = 108$). Soil-biochar mixtures from the rainfall simulation were manually filled into steel cylinders (diameter 6 cm, volume 100 cm^3). Proper mixing and homogenization of biochar and soil substrate was again ensured. Different amounts of biochar amendment led to varying bulk soil density between 0.94 and 1.53 g cm^{-3}. The lowest bulk soil density was found in the silt loam samples with 10% of HTC-char addition, and the highest bulk soil density was found in the control treatment without biochar addition. The soil samples were saturated with Tymolwater by capillary rise for a week. Based on the obtained pressure stages, water retention curves were calculated (cf. [55]). The available water capacity was calculated as the difference between volumetric water contents at the matric potentials of −6 kPa and −1.5 MPa [39].

To investigate effects of biochar amendment on erodibility, a linear mixed effects (LME) model was calculated and tested with an ANOVA type 3 with Satterthwaite's method. To explain sand loss from splash cups for every substrate, biochar type, biochar size, and the biochar application rate given as weight percentage were fitted as fixed effects, while the position under the simulator was fitted as random effect. All data was log-transformed before modeling, and the residuals did not show any deviation from normality. To investigate effects of biochar amendment on soil water movement for every substrate, further linear mixed effects models were calculated and tested with an ANOVA type 3 with Satterthwaite's method. To explain soil hydraulic conductivity and available water capacity, a first model was fitted for each target variable, including the whole data set, and using substrate, bulk soil density, biochar type, biochar particle size, and the biochar application rate as fixed effects. To further refine the outcome, a second model was fitted with soil hydraulic conductivity and available water capacity for each substrate separately. Here, biochar type, biochar size, and the biochar application rate were fitted as fixed effects. All data was log-transformed before modeling, and the residuals did not show any deviation from normality. Statistical significance was assumed at a level of alpha of 0.10. Statistics were performed with R 3.5.0 [56] and the R-packages "multcomp" [57] and "lmerTest" [58]. Graphs were produced with the R-package "ggplot2" [59].

3. Results and Discussion

3.1. Influence of Biochar on Soil Erodibility

Biochar had a significant effect on substrate losses in both silt loam and coarse sand treatments, but the effect was stronger with silt loam (Table 2). Furthermore, the particle size of the biochar, but not the application rate, affected soil losses in coarse sand. Both parameters, however, did not play a role for erodibility of the silt loam treatment.

Table 2. Results of the linear mixed effects (LME) model with Satterthwaite's method on substrate loss from splash cups for two substrates after rainfall simulation (n = 228).

	df [1]	F [2]	Pr [3]	sig [4]
Silt loam				
Biochar	97	9.1	0.001	***
Particle size	97	0.9	0.406	ns
Application rate	97	1.0	0.386	ns
Coarse sand				
Biochar	100	6.8	0.002	**
Particle size	100	7.2	0.001	**
Application rate	100	0.001	0.995	ns

[1] df: degree of freedom, [2] F: F value, [3] Pr: probability, [4] sig: significance, significance codes: *** = $p < 0.001$; ** = $p < 0.01$; ns = not significant.

With and without biochar amendment, the loam substrate showed mass losses about three times higher than the sand substrate (Figure 2). Sand loss was 34% lower with HTC-char (0.63 g) and 43% lower with Pyrochar (0.55 g), compared to sand treatments without biochar (0.96 g). Silt loss was 16% lower with HTC-char (1.83 g) and 22% lower with Pyrochar (1.70 g), compared to silt treatments without biochar (2.17 g). For both substrates, losses were lower with Pyrochar ($p < 0.001$), compared to HTC-char ($p < 0.01$) (Figure 2).

The particle sizes of biochar affected substrate losses differently, but only showed significant effects with coarse sand (Figure 3). Sand with biochar particle sizes of 1–2 mm (HTC and Pyrochar) showed lowest losses. At the same time, the application rate of biochar (2%, 6%, 10%) did not affect the erodibility of any substrate.

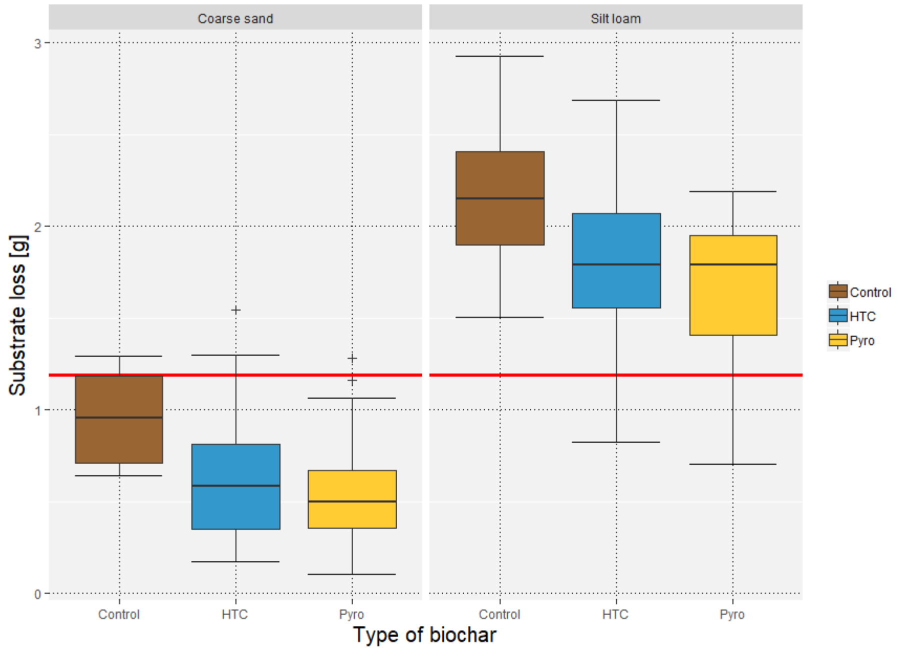

Figure 2. Influence of biochar amendment with two biochar types (HTC and Pyrochar + control treatment) on material loss from splash cups with coarse sand and silt loam. The red line signifies the mean material loss for all measurements (n = 228).

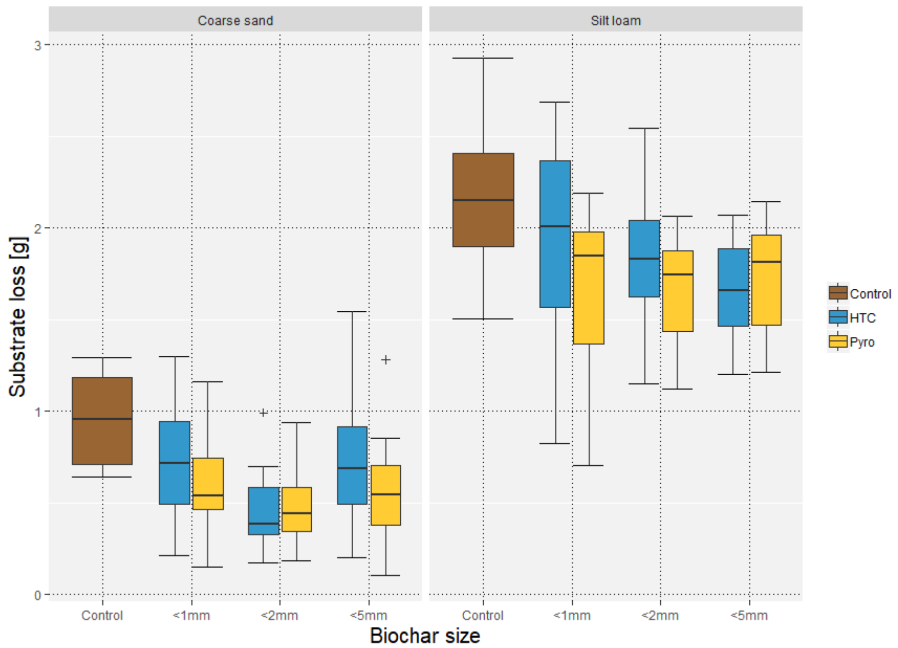

Figure 3. Influence of biochar amendment with two biochar types (HTC and Pyrochar + control treatment) and three different biochar sizes on material loss from splash cups with coarse sand and silt loam (n = 228).

The addition of biochar lowered the erodibility through splash erosion of both substrates directly after incorporation. The tested substrate surfaces included particle sizes up to 1 mm (sand) and 0.2 mm (silt), respectively. By adding a new and coarser particle size class to the substrates, the stability of the surfaces against the impact of raindrops was enhanced [35,60]. Shear stresses within the soil particles, which result from radially escaping water from the raindrops when they hit the soil surface, are mitigated by large, granular, gravel-sized particles [25,35]. Also, high pressures caused by raindrop impacts are mitigated [61]. This effect was even more pronounced in the non-aggregated test substrates of this experiment. The greater effect of biochar in the silt substrate, compared to the coarser sand substrate, can also be explained by the lack of aggregation [62,63].

Even though the introduction of a larger particle size class in itself had a clear effect on erodibility, patterns of different size classes within the biochar particles were not evident. A trend in erosion reduction could be traced within the silt loam treatment with increasing particle sizes of the biochar. Surprisingly, this did not show up as significant with our statistical approach in this finer substrate. Within the sand substrate, a positive effect could be stated, due to the differences of substrate loss in size classes from 1–2 mm, even if substrate losses increased again with the greatest size class up to 5 mm. Possibly, the differences between individual size classes were small, and could not be verified with the measurement setup used. Interestingly, the erosion-reducing effect of initial biochar amendment was already achieved with a low application rate, and a further increase of biochar amendment showed no advantages in this experiment. This may be due to the short time between introduction of the biochar and measurements, and could possibly change over a longer period of the experiment [21]. Moreover, surfaces of fresh biochar have shown to be hydrophobic [1,64], which could also have an influence on erodibility and, thus, soil erosion, but is by now not investigated in detail.

Finally, mere raindrop impacts without surface runoff did not lead to strong preferential removal of biochar from the surface, as, for example, described by [29,30]. Less than 1% of the total particles ejected consisted of biochar particles in every treatment. This was mostly due to the application strategy, as the biochar particles were not scattered, but actively incorporated into the substrate. To better understand preferential removal of biochar particles by rain splash action, corresponding experiments with different application methods and with different biochar size classes under simulated rainfall are recommended. The assumptions drawn from this experiment, however, only characterize the early stage after biochar amendment, as longer-term effects from different types of biochar are likely to arise. Further studies need to test biochar amendment in developed soils to include soil aggregation and effects of, for example, soil organic matter to the experimental design. Further effects can occur in later stages from adsorption properties of the biochar [21] and the associated formation of larger soil-biochar aggregates [65]. Thus, long-term field monitoring with biochar amendment to developed soils is necessary to further explain effects on (initial) soil erosion. These experiments should include biogeochemical factors and, particularly, processes of soil aggregation. At the same time, further studies should examine, in more detail, the erodibility properties of individual biochars from different productions.

3.2. *Influence of Biochar on Soil Water Movement*

Soil hydraulic conductivity and soil water retention differed importantly between the coarse sand and the silt loam treatment, with a mean soil hydraulic conductivity of 78 mm h^{-1} and 0.7 mm h^{-1}, respectively, and a mean available water capacity of 9.3% and 33.1%, respectively (Table 3). Results showed that soil hydraulic conductivity and the available water capacity increased in both substrates when biochar was added (Table 3). Both dependent variables increased with increasing biochar application rate, with the exception of the Pyrochar 2% treatment in silt loam. The highest conductivity value of 159 mm h^{-1} was measured in the sand treatment with 10% HTC-char amendment, whereas the silt treatment showed very low values down to 0 conductivity in the control and both 2% amendment treatments. Both dependent variables were most importantly affected by the substrate (both $p < 0.001$ ***) and bulk soil density ($p < 0.001$ *** and $p = 0.004$ **, respectively), which is in turn affected by biochar addition. Soil hydraulic conductivity was further affected by the application rate ($p = 0.006$ **) and the biochar type ($p = 0.018$ *), whereas the available water capacity did not show any further effects for both substrates together.

Table 3. Bulk soil density (g cm^{-3}), hydraulic conductivity (mm h^{-1}) and soil water retention characteristics (%) for silt loam and coarse sand (n = 108) with HTC-char, Pyrochar, and control (no biochar). FC_{min}: field capacity minimum (−6 kPa), PWP: permanent wilting point (−1.5 MPa), available water capacity: difference between volumetric water contents at the matric potentials of −6 kPa and −1.5 MPa.

Amendment	Bulk Soil Density	FC_{min}	PWP	Available Water Capacity	Hydraulic Conductivity
Coarse sand					
Control	1.50	4.51	1.12	3.39	35.56
Pyrochar 2%	1.42	5.43	1.26	4.17	44.45
Pyrochar 6%	1.33	11.26	2.29	8.98	46.31
Pyrochar 10%	1.19	15.88	6.25	9.63	96.01
HTC-char 2%	1.39	7.68	2.32	5.36	45.55
HTC-char 6%	1.20	16.36	3.41	12.95	88.90
HTC-char 10%	1.08	21.98	5.64	16.34	159.43
Silt loam					
Control	1.25	49.71	17.30	32.41	0.00
Pyrochar 2%	1.23	49.13	18.98	30.14	0.00
Pyrochar 6%	1.15	50.13	16.56	33.57	0.00
Pyrochar 10%	1.06	49.81	17.24	32.58	0.85
HTC-char 2%	1.20	50.15	17.54	32.61	0.00
HTC-char 6%	1.05	51.95	18.04	33.91	0.76
HTC-char 10%	0.96	54.28	18.34	35.94	2.79

If coarse sand and silt loam were investigated separately (Tables 3 and 4), increasing trends of both soil hydraulic conductivity and soil water retention were visible with increasing biochar application rate for every substrate. Again, the available water capacity in silt loam with 2% Pyrochar was an exception. Control treatments showed lowest values for both parameters, and, at the same time, highest values for bulk soil density.

Table 4. Results of the linear mixed effects (LME) model with Satterthwaite's method on soil water retention, given as the difference between volumetric water contents at the matric potentials of −6 kPa and −1.5 MPa (available water capacity) for silt loam and coarse sand (n = 108).

	Soil Hydraulic Conductivity			Available Water Capacity		
	F [1]	Pr [2]	sig [3]	F [1]	Pr [2]	sig [3]
Silt loam						
Biochar	16.3	<0.001	***	2.2	0.141	ns
Particle size	1.2	0.318	ns	0.6	0.576	ns
Application rate	25.7	<0.001	***	3.1	0.070	.
Coarse sand						
Biochar	31.7	<0.001	***	31.7	<0.001	***
Particle size	0.9	0.429	ns	0.9	0.429	ns
Application rate	45.7	<0.001	***	45.7	<0.001	***

[1] F: F value, [2] Pr: probability, [3] sig: significance, significance codes: *** = $p < 0.001$; . = $p < 0.1$; ns = not significant.

Increasing hydraulic conductivity and available water capacity in both substrates with biochar amendment (Figure 4) is in congruence with other studies, where the soil water movement was significantly improved regarding soil erosion control with biochar added to sandy and loamy soils [17,21,66]. The reason for increased infiltration, moisture retention, and available water capacity is due to changes in bulk surface area, pore-size distribution, packing, and density, due to the addition of biochar particles and a new particle size class to the given substrates [67,68]. In this experiment, it was observed that bulk soil density decreased in both substrates, and most visibly in the silt loam samples, when higher amounts of biochar were added (cf. [68]). Furthermore, it was shown that finer biochar particles can clog existing pores, and that properties of the biochar might enhance the amount of micropores [16]. Therefore, the amount of biochar added affects the micropore surface area and, thus, the water retention [16,69]. Similarly, Głąb et al. [40] found that higher addition of biochar and smaller biochar particle sizes increased the available water capacity. This finding could be partly confirmed by this study, as the application rate of biochar added to the substrates showed highly significant influences on substrates and bulk soil density, but particle sizes did not affect soil hydraulic conductivity or water retention at any measured matric potential (Tables 3 and 4). In both substrates, the type of biochar also affected soil hydraulic conductivity and, partly, the available water capacity, with the exception of the silt loam treatment (Table 4). This finding confirms other biochar studies on infiltration and water retention [66,70], and underlines the importance of the differences due to varying methods in biochar production. Since the effect on the available water capacity in silt loam is mainly due to the drop in values of one treatment (Pyrochar 1–2 mm), for which no replicate could be run due to a limited amount of particles available, a measurement error may be present here. On the other hand, it should be noted that the erodibility measurements also showed a significantly weaker expression in silt loam. This can therefore also be a systematic effect.

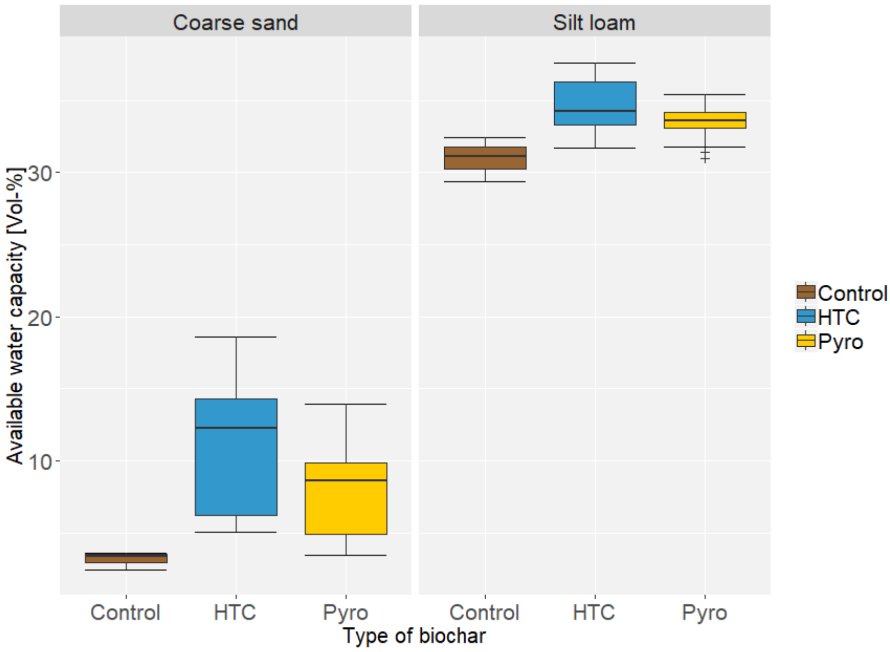

Figure 4. Soil water retention, given as the difference between volumetric water contents at the matric potentials of −6 kPa and −1.5 MPa (available water capacity) for coarse sand and silt loam with HTC-char, Pyrochar, and control (no biochar) (n = 108).

Results showed that for both substrates, the mean and range of the saturated hydraulic conductivity and the available water capacity differed between HTC-char and Pyrochar. This difference could be underpinned by the LME model (Tables 3 and 4 and Figure 4). The effect might be due to the different combustion (cf. [44]), as HTC-char was produced through hydrothermal carbonization at temperatures of 200 °C, while Pyrochar was generated through pyrolysis at temperatures of 700 °C [47]. As biochar characteristics are strongly influenced by the production processes and the handling of the biomass before and during the production [67,71,72], those varying characteristics could explain the differences. Downie et al. [67] also stated that the structure of the used biomass is imprinted on the biochar and, thus, affects the properties of the biochar and its effect on physical properties of the soil. As both biochars were produced in different laboratories using green waste for the production (with the term “green waste” being not clearly defined), the properties of the biochar might be different due to varying quality of the original material. This was also indicated by Burrell et al. [18], who found that biochars made from different feedstock (woodchips and straw) had different effects on moisture content, and confirmed by Andrenelli et al. with biochar pellets [73]. However, further experiments on different biochar types and their optimal application rates are necessary to substantiate these findings [43].

4. Conclusions

In this study, it was shown that the addition of biochar significantly reduced splash erosion rates in both a coarse sand and a silt loam substrate immediately after application. Thus, the first hypothesis can be accepted. Furthermore, in both substrates, greater biochar particle sizes partly showed lower erodibility. We conclude that this effect is strongly dependent on the substrate, and it is especially evident with larger soil particle sizes, whereas the type of biochar and different application rates are not important to mitigate splash erosion. Moreover, biochar amendment increased hydraulic conductivity and soil water retention, a result that confirms the second hypothesis. We could show that different biochar types influenced hydraulic characteristics, and biochar generally improved both parameters regarding soil erosion control, with increasing application rates. These effects have the potential to further enhance resilience against erosion and soil degradation in agriculture. This is already evident in a very early stage of amendment and without long-term incorporation of biochar into soils.

Recently, several studies have tried to shed light on how single mechanisms of soil erosion are affected by biochar amendment, and have tried to focus on the particle scale (e.g., [45,70]). This study further contributes to this topic, and encourages future studies focusing on small-scale effects. Understanding individual processes will increasingly help to recognize the overall relationship between biochar and soil erosion. In this context, it became clear that biochar differs due to its type and size. Further research with varying biochars produced with different production methods is required [43] to investigate influences of their properties on erosion-related parameters in more detail. Nevertheless, it can be assumed that the most significant influences take place over longer periods of time. Biochar amendment directly affects clay and organic matter content, improves the stability of aggregates against water and wind erosion, and further interacts with minerals and soil organisms over time [8,74]. Thus, experiments at field-scale, and with larger timescales, are likewise needed [21,22,75], to substantiate findings on particle transport and (initial) soil erosion in general.

In conclusion, this study showed that biochar amendments have the potential to reduce soil erosion by water from a very early stage. This mechanism adds a further ecosystem service to the list of useful impacts of biochar application on agriculture.

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