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Effect of Slope, Rainfall Intensity and Mulch on Erosion and Infiltration under Simulated Rain on Purple Soil of South-Western Sichuan Province, China

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Abstract: Purple soil is widely distributed in the hilly areas of the Sichuan basin, southwest China, and is highly susceptible to water erosion. The triggering of this process is related to slope, rainfall intensity and surface cover. Therefore, this study assesses the effects of different simulated rainfall intensities with different slopes on hydrological and erosional processes in un-mulched and mulched purple soils. Results show that the sediment and water losses increased with an increase of rainfall intensity and slope steepness. Generally, the slope contribution (Sc) on water and sediment losses decreased with increasing rainfall intensity and slope steepness under both un-mulched and mulched soil. In un-mulched conditions, water losses were independent of slope steepness (Sc < 50%) during the highest rainfall intensity. However, in mulched soil, the higher contributions of slope (Sc) and rainfall (Rc) were found for water and sediment losses, respectively, i.e., >50%, except during the increase in slope steepness from 15° to 25° under the highest rainfall intensity (120 mm·h^{-1}). The effectiveness of mulch was more pronounced in reducing sediment losses (81%–100%) compared with water losses (14%–100%). The conservation effectiveness of mulch both decreased and increased with slope steepness for water and sediment losses, respectively, under higher rainfall intensities. Water infiltration and recharge coefficient (RC) decreased with an increase of slope steepness, while with an increase in rainfall intensity, the water infiltration and RC were increased and decreased, respectively, in both un-mulched and mulched soil. On the other hand, mulched soil maintained a significantly (α = 0.05) higher infiltration capacity and RC compared to that of the un-mulched soil.

Keywords: slope; rainfall intensity; water erosion; infiltration rate; recharge coefficient; simulated rainfall

1. Introduction

Purple soil occurs widely in the hilly areas of the Sichuan basin. It is one of the valuable agricultural soil resources in China, and its inherent natural fertility and high capability makes it suitable for intensive crop production [1]. However, purple soil is highly susceptible to accelerated erosion, and soil and water losses are recognized among the major causes of land degradation [2]. Soils of the region are vulnerable to severe erosion because of steeper slopes and frequently intense rainfall throughout the year with a soil erosion rate of 3035 Mg/km^2 in the area [3].

Slope and rainfall intensities are important factors influencing the erosion processes [4,5]. The mobilization of soil particles during rain-splash erosion depends on rainfall intensity [6]. In contrast, the mobilization of solid particles is the result of overland flow. Thus, a major influence of slope on erosion appears to be exerted through its impact on runoff velocity [7,8] and sediment transport capacity of runoff has been reported to increase with increasing flow velocity [9]. Moreover, in rain impacted flows, detachment and transport processes are highly dependent on the dissipation of raindrop kinetic energy, and more of the raindrop energy is dissipated in the water layer as flow depth increases, leading to a decline in sediment concentration on gentle slopes [10]. Furthermore, antecedent soil moisture content can be one of the most important factors controlling hydrological and erosive processes [11–13] that affects the partitioning of rainfall into infiltration and runoff [12] and thus influences the soil erosion [14].

Mulching soil is one of the best management practices (BMPs) to control erosion on sloping lands [15,16] and the effectiveness of a wide range of mulch materials on reducing soil detachment and transport, and modifying hydraulic characteristics of runoff have been widely studied under simulated rainfall and field conditions [17]. However, the effectiveness of a mulch cover in minimizing water erosion depends on soil type, rainfall intensity, slope angle, types and rates of mulch application [18]. It was observed that mulching with elephant grass (*Pennisetum purpureum*) increased the infiltration rate and decreased soil sediment and runoff losses in three soil series (Apomu, Jago and Iwo) in western Nigeria under different rainfall intensities and slopes. Nonetheless, different soil types can have different responses due to differences in texture and organic matter content [19].

When rainfall begins, fine particles are detached from coarse particles, and carried downslope to form a crust [20] because mechanical breakdown and slaking are the primary mechanisms involved in crust formation [21], which is a common phenomenon in purple soil [21,22]. However, mulch protects the soil from the direct action of raindrops, reduces the erosive effect of rainfall, and effectively reduces crust formation [23]. Moreover, it increases soil water retention, delays runoff by increasing pathway tortuosity, increases infiltration rate, and decreases the sediment carrying capacity of the flowing water [24–26]. Thus, erosion hazards can be effectively reduced in covered purple soil. Some previous studies have described that in vegetation covered purple soil, overland flow [27] and sediment losses [2] were decreased by 19.1%–83.9% and 90% respectively, compared to bare soil. However, the effectiveness of wheat straw mulch to reduce runoff and sediment discharge has not yet been quantified for the purple soil. Therefore, this study was based on the hypothesis that (1) increase in rainfall intensity and slope steepness will increase the sediment and water losses and decrease infiltration rate (2) and wheat straw would decrease soil detachment by reducing the raindrop impact, increasing water infiltration and sediment filtration. The objectives of this study were therefore to (1) investigate the effects of a range of rainfall intensities and slope levels on water and sediment losses, infiltration and water recharge coefficient (RC) in un-mulched and mulched soils and (2) assess the effectiveness of wheat straw mulch in conserving water and soil sediment on sloping lands.

2. Materials and Methods

2.1. Experimental Equipment

The main experimental setup used in the study consists of a rainfall simulator and runoff trays (Figure 1). The simulator (model Dik-6000, Daiki Rika Kogyo Co., Ltd., Shiga, Saitama, Japan) is fitted with 324 nozzles (rain needles), which comprised of aluminum channels assembled in the steel frame. A vibration motor is attached to the frame, generating the desired raindrop size (1.7–2.8 mm) by adjusting the number of revolutions of the motor, which produces rainfall intensity that can be precisely adjusted by two flow meters. The experimental runoff trays mainly consist of iron trays and plastic containers. The size of the iron trays is 1 m × 0.3 m × 0.4 m (length × width × height) that can be adjusted to the desired slope angle using a jack. The plastic container of 10 L in volume was used to collect the runoff and sediments. It was set at the outlet of the runoff tray at the beginning of each rainfall simulation and changed several times in each interval. Finally, the total runoff volume of each interval was recorded.

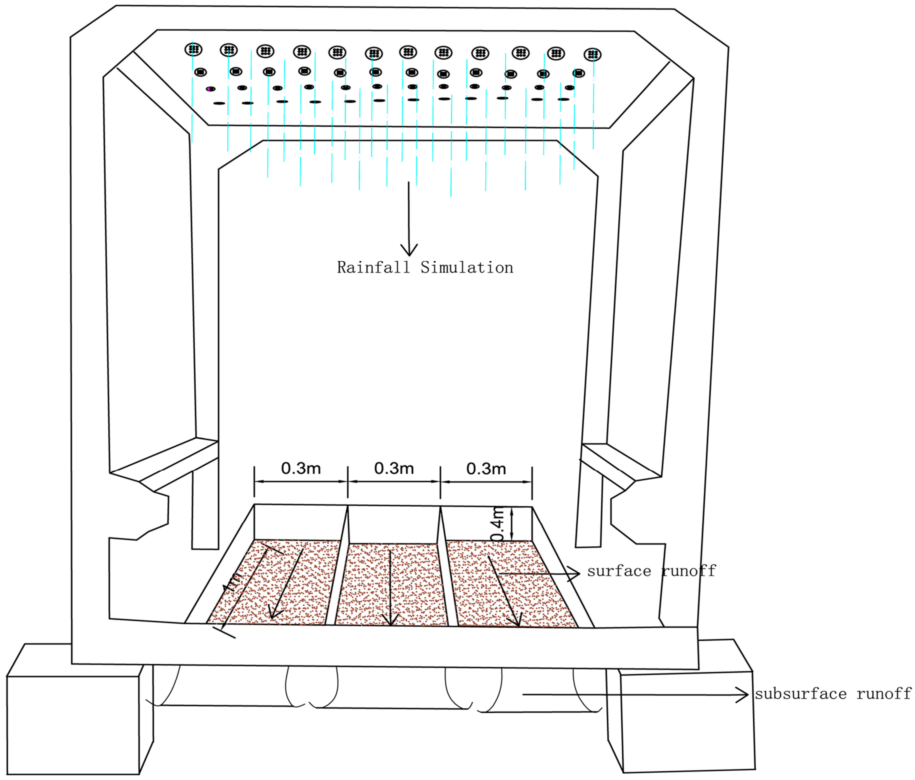

Figure 1. Rainfall simulator and runoff trays placement.

2.2. Experimental Treatments and Measurements

The rainfall simulation experiments were conducted on three slope (5°, 15°, 25°) under four rainfall intensities (33 mm·h^{-1}, 54 mm·h^{-1}, 94 mm·h^{-1}, 120 mm·h^{-1}), which are representative of slopes and rainfall intensities in the Sichuan basin, southwest China. The above-mentioned slope levels and rainfall intensities were used in all possible combinations both in mulched and un-mulched soils with three replicates, resulting in a total of 72 simulation runs.

Purple soil (Calcaric Regosols) was collected from the surface (0–15 cm depth) of Sichuan Province, southwest China. The soil texture was characterized as a silt loam type based on the United States Department of Agriculture (USDA) classification system. The particle size of the soil consisted of 91.4 g·kg^{-1} clay (0–2 µm), 425.9 g·kg^{-1} fine silt (2–20 µm), 250.9 g·kg^{-1} coarse silt (20–50 µm) and 232.5 g·kg^{-1} sand (>50 µm). The content of total soil organic carbon (SOC), total nitrogen (N), total phosphorus (P) and total potassium (K) were 19.36 g·kg^{-1}, 1.4 g·kg^{-1}, 0.53 g·kg^{-1} and 14.1 g·kg^{-1}, respectively. Before filling the trays with soil, the purple soil was passed through a 1 cm sieve after it had been gently crushed. In order to minimize the difference among treatments, the sieved soil was thoroughly mixed. A 3 cm thick layer of sand was poured at the bottom of the tray, and soil was poured on top of sand to a 30 cm depth. The soil was poured in subsequent layers, and compacted uniformly by using a wooden block to achieve a uniform compaction. The goal was to ensure the same soil moisture (20%) and compaction (500 kpa) levels during all simulated experiments. Each time antecedent soil moisture and compaction level was measured randomly from different points in each tray with the help of a portable soil moisture and compaction penetrometer (SL-TSA, Baziu Shiye, Shanghai, China). A needle probe and hand-held steel rod were attached to the digital meter by a cable to measure soil moisture and compaction, respectively. Soil moisture contents were adjusted by a commonly used household sprayer for each run [28]. In mulched treatments, wheat straw was uniformly distributed over the soil surface, and it completely covered the soil to 4 cm thickness. After finishing a rainfall event, the used soil was replaced from the trays and the trays were repacked with unused new soil and wheat straw mulch as described above for the next simulation run.

A rainfall simulator was attached to the source of the tap water to ensure a continuous supply of water. Prior to experiments, the simulator was calibrated for the desired intensity and the mean drop size of 2.7 mm. The duration for each rainfall event was one hour, and the rainfall simulator was adjusted at the height of 2 m above the soil surface. Runoff water from each run at 10-min interval was collected in plastic containers, and a standard measuring cylinder was used to record the runoff volume. The runoff water collected was settled for 48 h prior to decantation. Clear supernatant was decanted and sediment was filtered with the help of Whatman filter papers #42 and sun-dried. Afterward, the sediments were dried in an oven to a constant weight at 105 °C for determination of the dry sediment weight.

2.3. Calculations and Data Analysis

Contribution of slope and rainfall intensity in generating runoff and sediment losses were calculated using Equations (1) and (2) [29].

Total increment in losses with increase in slope steepness = $\mathrm{Ei} - \mathrm{e_o}$
Rainfall intensity increment = $\mathrm{ei} - \mathrm{e_o}$
Slope Increment = $\mathrm{Ei} - \mathrm{ei}$

$$\text{Rainfall contribution in losses (RC) \%} = \frac{\mathrm{ei} - \mathrm{e_o}}{\mathrm{Ei} - \mathrm{e_o}} \tag{1}$$

$$\text{Slope contribution in losses (SC) \%} = \frac{\mathrm{Ei} - \mathrm{ei}}{\mathrm{Ei} - \mathrm{e_o}} \tag{2}$$

where

ei = runoff or sediment losses under different rainfall intensities when the slope steepness remains unchanged (5° or 15°).
Ei = runoff or sediment losses at a higher slope under different rainfall intensities when the slope steepness changed from 5° to 15° or 15° to 25°.
$\mathrm{e_o}$ = values of runoff or sediment losses during rainfall intensity of 33 $\mathrm{mm \cdot h^{-1}}$ at 5° and 15° slopes during an increase in steepness from 5° to 15° and 15° to 25°, respectively.

Statistical analyses were conducted in SPSS 16.0 for Windows (SPSS Inc., Chicago, IL, USA). An analysis of variance (ANOVA) test was used to determine the treatment effects on the measured variables. An LSD (Least significant difference) test ($\alpha = 0.05$) was performed for the means comparison both in un-mulched and mulched treatments, separately. Linear regression analysis was performed to develop an equation for recharge coefficient (RC). Figures were drawn using Origin pro 9.0 (Origin Labs Corporation, Northampton, MA, USA).

3. Results and Discussions

3.1. Surface Runoff

In un-mulched soil, the runoff was significantly affected by rainfall intensity and slope steepness i.e., runoff was increased with increasing rainfall intensity and slope steepness (Table 1). The minimum and maximum runoff of 0.2 and 68.1 $\mathrm{mm \cdot m^{-2}}$, respectively, were recorded during the lowest rainfall intensity under the lowest slope and highest rainfall intensity with the steepest slope, respectively. Slope is an important factor influencing the runoff generation process [4,5]. It strongly affects the water storage on the soil surface [30,31]. Therefore, changes in slope steepness could alter the runoff process. The results show that the effect of slope on the runoff varied with the rainfall intensity (Table 1). Runoff significantly (α = 0.05) increased with increase in slope steepness during all rainfall intensities in un-mulched soil. However, an increase in slope steepness from 5° to 15° had a non-significant effect on runoff under the rainfall intensities of 120 mm·h^{-1}, because during higher rainfall intensities, the time required for runoff generation was too short to reflect the difference between slopes [32]. Whereas, the same slope steepness (increase from 5° to 15°) with a rainfall intensity of 94 mm·h^{-1} had a significant effect on runoff. The effect could be due to the permeable conditions of soil, which absorbed more water during lower rainfall intensity, and delayed runoff on 5° slopes.

Table 1. Mean runoff loss (mm·m^{-2}) values under various rainfall intensities and slopes in un-mulched and mulched soil.

Treatments	Slope (°)	Rainfall Intensity (mm·h^{-1}) Runoff								ANOVA
		33		54		94		120		
		Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	
Un-mulched	5	0.2 ^{b,C}	0.02	2.5 ^{c,C}	0.40	23.0 ^{c,B}	1.05	52.4 ^{b,A}	3.84	$p < 0.01$
	15	1.5 ^{a,B}	0.09	7.1 ^{b,B}	0.13	49.6 ^{b,A}	7.30	56.6 ^{b,A}	4.01	$p < 0.01$
	25	1.7 ^{a,D}	0.21	19.2 ^{a,C}	2.44	60.5 ^{a,B}	1.90	68.1 ^{a,A}	5.73	$p < 0.01$
	ANOVA	$p < 0.01$		$p < 0.01$		$p < 0.01$		$p < 0.05$		
Mulched	5	0.00 ^{b,C}	0.00	0.00 ^{c,C}	0.00	3.7 ^{c,B}	0.13	7.3 ^{c,A}	0.57	$p < 0.01$
	15	0.00 ^{b,C}	0.00	1.17 ^{b,C}	0.07	15.9 ^{b,B}	1.07	30.9 ^{b,A}	3.62	$p < 0.01$
	25	0.50 ^{a,C}	0.03	3.38 ^{a,C}	0.28	34.1 ^{a,B}	4.70	58.4 ^{a,A}	5.81	$p < 0.01$
	ANOVA	$p < 0.01$		$p < 0.01$		$p < 0.01$		$p < 0.01$		

Notes: Mean values (n = 3) are given with standard deviation (S.D). Small letters ($^{a-c}$) are to be read column-wise and capital letters ($^{A-D}$) row-wise. Values followed by dissimilar letters are significantly different at 0.05 using an LSD test.

The effect of increasing rainfall intensities at a specific slope level was also compared and different patterns of runoff generation were recorded at different slope levels (Table 1). The runoff losses significantly (α = 0.05) increased with an increase in the rainfall intensities from 33 to 120 mm·h^{-1} at all slope levels, however, there was a non-significant change in runoff between rainfall intensity of 33 mm·h^{-1} and 54 mm·h^{-1} at 5° and 15° slopes. When rainfall begins, surface depressions progressively overflow and are connected to nearby depressions resulting in overland flow [30,33,34]. This process starts when the infiltration capacity during a rainfall event is lower than the rainfall intensity [35]. The data of the present study show that a lower slope reduced any overflow from depressions, and resulted in non-significant runoff generation between rainfall intensity of 33 and 54 mm·h^{-1} (Table 1). Therefore, a great part of the rainfall infiltrated and delayed the runoff generation during rainfall events of low intensity. Therefore, any further increase in rainfall intensity exceeded the rate of infiltration and resulted in significant runoff losses [36]. However, at steepest slope (25°), the runoff losses were significantly different even for lower rainfall intensities (33 and 54 mm·h^{-1}) due to an increase and decrease in gravitational force and the soil's water retention ability, respectively (Table 1). Similar results have been reported in other studies [37].

The results, in Figure 2, indicate the contribution of rainfall (Rc) and slope (Sc) on runoff losses during different rainfall intensities with different slope steepness. The Sc was 100% during the rainfall intensity of 33 mm·h^{-1} with an increase in slope steepness from 5° to 15° and 15° to 25°. The higher Sc of >50% was found for rainfall intensities of 33 mm·h^{-1} and 54 mm·h^{-1} with an increase in slope steepness from 5° to 15° and 15° to 25°. However, Sc was higher (>50%) and lower (<50%) during rainfall intensity of 94 mm·h^{-1} with an increase in slope steepness from 5° to 15° and 15° to 25°, respectively. Moreover, the lower Sc (<50%) was found for rainfall intensity of 120 mm·h^{-1} with an increase in slope steepness from 5° to 15° and 15° to 25°. Thus, results show that with an increase of rainfall intensity and slope steepness, the Sc and Rc were decreased and increased, respectively.

When the Sc becomes negligible, then it indicates the critical level where runoff losses are only depending on rainfall intensity. A previous study reported that; 'there exists a critical slope above or below of it, the runoff exhibits different behavior' [29], and when slope angle is less than a critical threshold, runoff rate increases greatly with slope, while when the slope is steeper than the critical threshold, the runoff rate is less influenced by slope [38,39]. However, the results herein show that the critical slope level could vary with rainfall intensities (Figure 2), and be achieved earlier for intense rainfalls as compared with gentler rainfall intensities.

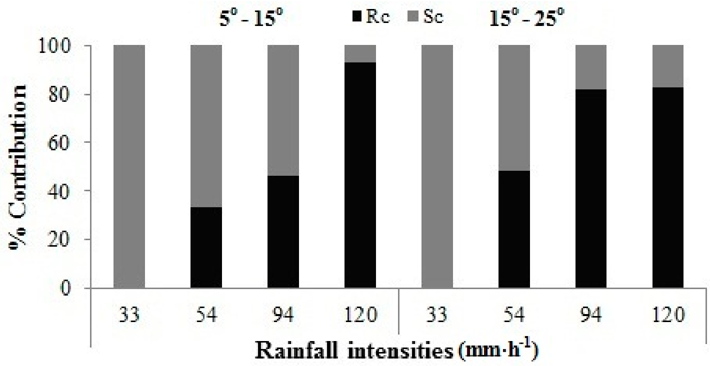

Figure 2. Rainfall (Rc) and slope (Sc) contributions for runoff losses under different rainfall intensities with increasing slope steepness from 5° to 15° and 15° to 25° in un-mulched soil.

In mulched soil, the runoff losses increased with increasing rainfall intensity and the slope steepness. The results, in Table 1, indicate that the maximum runoff of 58.4 mm·m^{-2} was recorded for the rainfall intensity of 120 mm·h^{-1} at the 25° slope level. Under rainfall simulations of 33 mm·h^{-1}, runoff was completely stopped, while negligible losses occurred at 15° and 25° slope during rainfall intensity of 54 mm·h^{-1}. The results, in Figure 3, indicate that Sc for runoff losses was >50% during an increase in slope steepness from 5° to 15° under rainfall simulation of 54, 94 and 120 mm·h^{-1}. However, Sc was >50% with an increase in slope steepness from 15° to 25°, except for rainfall simulations of 120 mm·h^{-1}. These results suggest that mulch tended to retard the flow velocity, and reduced the quantity of water available for runoff losses, thus slope becomes an important factor influencing the runoff generation in mulched conditions. However, Sc values showed a decreasing trend with increasing rainfall intensity and slope steepness; this trend shows water absorbing and flow reducing capacity of mulch decreases with increasing rainfall intensity and slope steepness. Thus, Sc for runoff losses in mulched soil decreases accordingly. Because runoff on steep slopes is greater, primarily because water remains for a shorter time on the soil because of the gravity effect, and reduced water storage capacity [40].

Straw mulch significantly ($\alpha = 0.05$) reduced runoff volume as compared with the un-mulched treatments (Figure 4a), indicating that a portion of rainfall was either infiltrated into the soil or absorbed by the straw covered surface. The capacity of air-dried residues to absorb water up to 4.8 times its original weight [41]. Moreover, the conservation effect of straw mulch reduced with increasing slope steepness during higher rainfall intensities (Figure 4a). The minimum reduction of 14% was observed for the rainfall intensity of 120 mm·h^{-1} at the 25° slope level. These trends indicate that a reduction in runoff losses decreased with an increase in rainfall intensity in mulch treatments at a steep slope. Similar findings have been reported by other researchers, who also observed that increasing slope steepness was the important factor in runoff losses even in the presence of mulch cover [19,42]. However, some researchers [42] reported that straw mulch (600 g·m^{-2}) had no runoff during rainfall of 30 mm·h^{-1} on both 10° and 20° slopes, and negligible runoff in a simulation of 60 mm·h^{-1} on the 10° slope. The data from the present study also show that mulching decreases runoff losses (Figure 4a). However, these data indicate that the application of straw mulch to 4 cm thickness during low rainfall intensity may not be economical. Indeed, runoff losses from un-mulched soil during lower rainfall intensity were negligible compared to those under higher rainfall events. During low rainfall intensities, more rainfall is intercepted by thicker mulches, and also partly influences soil water conservation [43]. However, there was threshold mulch thickness to avoid excessive water interception during low-intensity rainfalls [44]. Although the magnitude of reduction in runoff losses decreased with an increase in slope during high-intensity rains, the reductions were significant. These results conclusively demonstrate the effectiveness of straw mulch in reducing runoff losses.

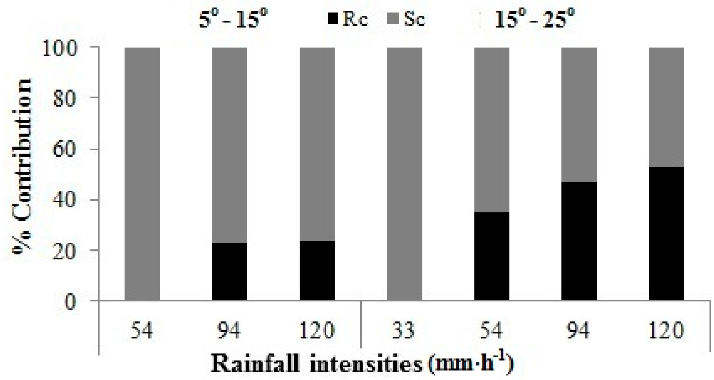

Figure 3. Rainfall (Rc) and slope (Sc) contributions for runoff losses under different rainfall intensities with an increase in slope steepness from 5° to 15° and 15° to 25° in mulched purple soil.

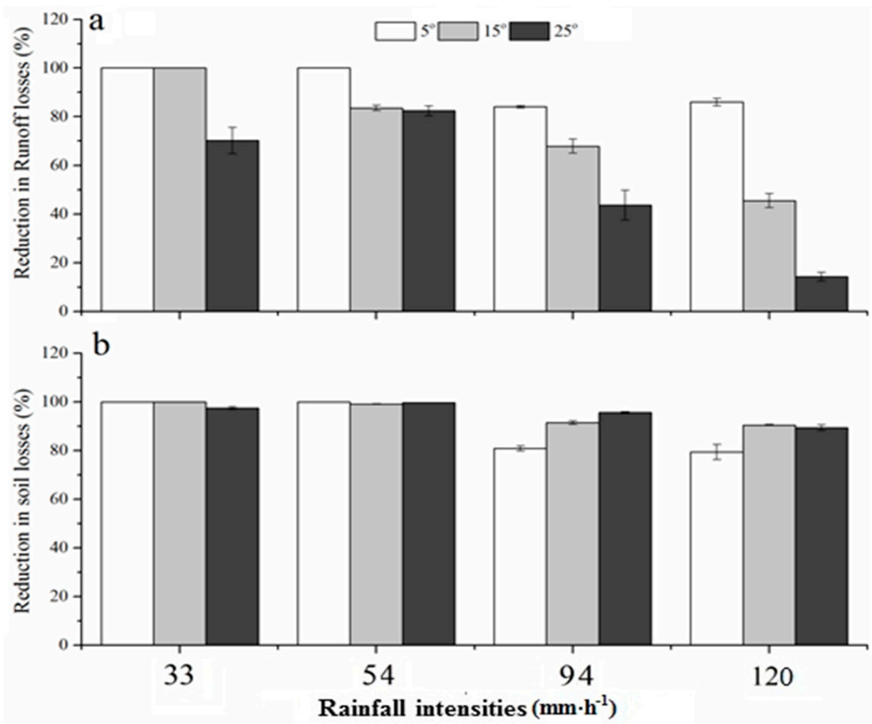

Figure 4. Conservation effectiveness of straw mulch on (**a**) runoff losses and (**b**) sediment losses from purple soil. Mean values (n = 3) are given with standard deviation (S.D).

3.2. Sediment Losses

Rainfall intensity and slope significantly influenced sediment losses under un-mulched and mulched treatments (Table 2), which increased with an increase in rainfall intensity and slope steepness. With higher slopes, sediment losses were similar for the rainfall intensity of 94 and 120 mm·h^{-1} in un-mulched soil (Table 2). The maximum sediment loss of 876.2 g·m^{-2} was observed for un-mulched soil under the rainfall intensity of 94 mm·h^{-1} at the 25° slope (Table 2). Slope is an important control of sediment loss [29], as is also shown by the data presented herein. Soil detachment is strongly influenced by the raindrop impact, whereas the detached soil particles are transported by the combined action of the thin sheet flow and raindrop impact [45]. Moreover, the presence of a water layer on the soil surface controls the detachment rate [46]. As a result, the dissipation of raindrop kinetic energy greatly influences the detachment and transport processes in rain impacted flows, and more of the raindrop energy is dissipated in the water layer as flow depth increases, leading to a reduction in the soil erosion rate [10]. Thinner flow depth on the soil surface exposes the aggregates to raindrop impact and exacerbates the sediment losses on steep slopes (Table 2). With the buffering effect of the water layer on raindrop impact, the inter-rill or the splash erosion is decreased on gentler than that on steeper slopes [47]. Thus, increase in slope steepness significantly increased sediment losses at steeper slopes for all rainfall intensities (Table 3). Furthermore, detached soil particles are easily entrained by higher flow velocity and stream power on steeper slopes [45,48–50].

Table 2. Mean sediment loss (g·m^{-2}) values under various rainfall intensities and slope levels in un-mulched and mulched soil.

Treatments	Slope (°)	Rainfall Intensity (mm·h^{-1})								ANOVA
		33		54		94		120		
		Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	
Un-mulched	5	0.43 ^{c,C}	0.10	23.5 ^{c,C}	4.8	111.2 ^{c,B}	6.60	184.5 ^{b,A}	24.7	$p < 0.01$
	15	3.60 ^{b,C}	0.60	84.6 ^{b,B}	5.1	382.1 ^{b,A}	37.8	387.0 ^{b,A}	76.8	$p < 0.01$
	25	5.79 ^{a,C}	1.50	220.0 ^{a,B}	35.0	876.2 ^{a,A}	76.3	849.4 ^{a,A}	162.4	$p < 0.01$
	ANOVA	$p < 0.01$		$p < 0.01$		$p < 0.01$		$p < 0.01$		
Mulched	5	0.00 ^{b,C}	0.00	0.00 ^{b,C}	0.00	21.26 ^{c,B}	0.17	31.03 ^{b,A}	3.19	$p < 0.01$
	15	0.00 ^{b,C}	0.00	0.73 ^{a,C}	0.08	26.88 ^{b,B}	0.95	36.84 ^{b,A}	7.57	$p < 0.01$
	25	0.43 ^{a,C}	0.03	0.85 ^{a,C}	0.07	34.69 ^{a,B}	2.35	88.63 ^{a,A}	8.75	$p < 0.01$
	ANOVA	$p < 0.01$		$p < 0.01$		$p < 0.01$		$p < 0.01$		

Notes: Mean values (n = 3) are given with standard deviation (S.D). Small letters ($^{a–c}$) are to be read column-wise and capital letters ($^{A–C}$) row-wise. Values followed by dissimilar letters are significantly different at 0.05 using an LSD test.

Table 3. Mean water infiltration (mm·m^{-2}) values under various rainfall intensities and slope levels in un-mulched and mulched soil.

Treatments	Slope (°)	Rainfall Intensity (mm·h^{-1})								ANOVA
		33		54		94		120		
		Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	
Un-mulched	5	32.8 ^{a,C}	0.02	51.5 ^{a,B}	0.40	70.9 ^{a,A}	1.05	67.6 ^{a,A}	3.84	$p < 0.01$
	15	31.5 ^{b,C}	0.09	46.9 ^{b,B}	0.13	44.4 ^{b,B}	7.30	63.4 ^{a,A}	4.01	$p < 0.01$
	25	31.3 ^{b,B}	0.21	34.8 ^{c,B}	2.44	33.5 ^{c,B}	1.90	51.9 ^{b,A}	5.73	$p < 0.01$
	ANOVA	$p < 0.01$		$p < 0.01$		$p < 0.01$		$p < 0.05$		
Mulched	5	33.0 ^{a,D}	0.00	54.0 ^{a,C}	0.00	90.3 ^{a,B}	0.13	112.7 ^{a,A}	0.57	$p < 0.01$
	15	33.0 ^{a,D}	0.00	52.8 ^{b,C}	0.07	78.1 ^{b,B}	1.07	89.1 ^{b,A}	3.62	$p < 0.01$
	25	32.5 ^{b,C}	0.03	50.6 ^{c,B}	0.28	59.9 ^{c,A}	4.70	61.6 ^{c,A}	5.81	$p < 0.01$
	ANOVA	$p < 0.01$		$p < 0.01$		$p < 0.01$		$p < 0.01$		

Notes: Mean values (n = 3) are given with standard deviation (S.D). Small letters ($^{a–c}$) are to be read column-wise and capital letters ($^{A–D}$) row-wise. Values followed by dissimilar letters are significantly different at 0.05 using an LSD test.

Comparing the effect of increasing rainfall intensity at a specific slope level (Table 2), data show that an increase in sediment losses by increasing rainfall intensity were maximum at the lowest slope; it created more sediment loss, whereas this effect decreased, at steeper slopes. With an increase from lower (33 mm·h^{-1}) to higher (120 mm·h^{-1}) rainfall intensity, sediment loss increased significantly at the 5° slope. However, at higher slopes, it increased significantly up to rainfall intensity of 94 mm·h^{-1} (Table 2). At the steepest slope, increase in runoff was significant due to increasing rainfall intensity, but the sediment loss was almost the same. During rainfall simulation of 94 mm·h^{-1} at the 25° slope, the sediment loss of 876.2 g·m^{-2} was significantly higher than that of 387 g·m^{-2} for the rainfall intensity of 120 mm·h^{-1} at the 15° slope (Table 2). These datasets indicate that soil vulnerability to erosion changes with change in slope angle, and during an intense storm, the soil erosion process is strongly affected by slope steepness. Therefore, during higher rainfall events, intensity is the principal control that affects the runoff process and slope is the dominant control, which affects sediment loss in un-mulched soil. However, other studies have shown that increases in rainfall intensity had a non-significant effect on soil sediment yield at higher slopes during intense rainfall events in bare or un-mulched soil [37,51].

The results, in Figure 5, indicate the contribution of rainfall (Rc) and slope (Sc) on sediment losses for different rainfall intensities and different slope steepness. In un-mulched conditions, the contribution of slope to generate sediment loss was >50% for all rainfall intensities, which decreased with an increase in rainfall intensity (Figure 5). The rainfall intensity of 33 mm·h^{-1} had no contribution to sediment loss, even with an increase in slope steepness. While a further increase in rainfall intensity resulted in decreased contribution of slope to the sediment loss, the contribution of slope and rainfall was almost equal at the highest rainfall intensity (Figure 5). Therefore, the contribution of slope to sediment loss depends on rainfall intensity. Under the rainfall intensity of 54 and 94 mm·h^{-1}, contribution of slope to produce sediment was higher when the slope angle was increased from 5° to 15° compared with that from 15° to 25° (Figure 5). This trend indicates that although increasing slope steepness affects soil erosion, the effect of increasing slope in contributing to soil sediment losses decreases for the steepness beyond the critical slope. These results are in accord with the other study, which also reported that the effect of slope on soil erosion decreased beyond the critical slope level [29].

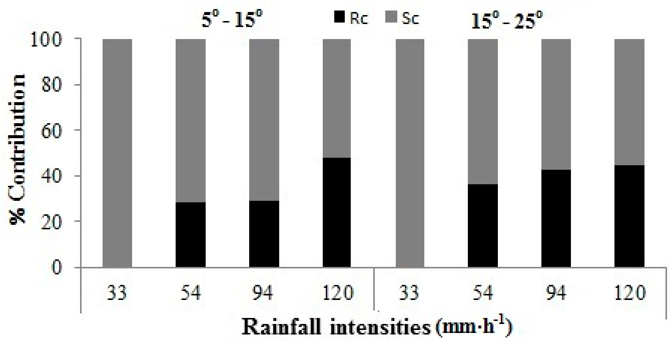

Figure 5. Rainfall (Rc) and slope (Sc) contributions for sediment losses under different rainfall intensities with increasing slope steepness from 5° to 15° and 15° to 25° in un-mulched purple soil.

Sediment losses were almost negligible under mulched conditions with lower rainfall intensities (Table 2), and a significant increase in sediment losses occurred with increasing slope steepness from 5° to 25°. The maximum sediment loss of 88.63 g·m^{-2} was observed for the simulated rainfall intensity of 120 mm·h^{-1} at the 25° slope (Table 2). The results presented in Figure 6, regarding the contribution of rainfall (Rc) and slope (Sc) for sediment losses in mulched soil indicate that for rainfall intensities of 54 mm·h^{-1} and 33 mm·h^{-1}, Sc was 100% with an increase in slope steepness from 5° to 15° and 15° to 25°, respectively. Thus, in that situation where runoff was negligible, sediment loss was strongly controlled by the slope. However, due to an increase in slope steepness for higher rainfall intensities, Rc was the main factor that controlled the sediment loss (Figure 6), because the effect of impacting raindrops was diminished by the mulch cover [52]. Therefore, the erosional process was primarily controlled by shallow flow under the mulch surface. In this context, effective erosion control materials are those which provide cover to intercept the rainfall and retard the sheet flow velocity [15].

A large proportion of water was infiltrated in soil under lower rainfalls and in mulched conditions. Consequently, with the lower amount of runoff, the amount of surface storage was primarily controlled by the slope angle. However, during the high intensity events, flow velocities were large enough to overcome the retarding effect of mulch, and the sediment loss by runoff was affected by the rainfall (Figure 6). Thus, higher flow velocities and the scouring ability of sheet flow beneath the mulch surface could be the reason for high sediment loss during intense rainfall events. In field experiments [53], researchers have demonstrated that in un-mulched plots, sediment loss increased exponentially with increasing slope steepness, while this trend could not apply in mulched plots due to the interception of rainfall energy by the mulch.

Mulch significantly (α = 0.05) reduced (81% to 100%) the sediment losses relative to the un-mulched control (Figure 4b), because unprotected purple soil is more vulnerable to erosion compared to other soil types. Nonetheless, the sediment loss during rain events could decrease up to 90% with the vegetation cover of up to 80% [2]. Mulching strongly reduced sediment loss at higher rainfall intensities and slopes relative to reductions in runoff loss (Figure 4b). This trend indicates that straw mulch filtered sediment from the runoff water, and reduced the sediment loss which was negligible even at the 25° slope during rainfall intensity of 120 mm·h^{-1}. Despite the minimal sediment loss, only 14% reduction in runoff generation was observed for the same rainfall intensity and slope (Figure 4a,b). On steeper slopes, gravitational force accelerates the runoff flow but decreases sediment loss, because of the retention of soil particles within the mulch (Figure 4b). Thus, an unequivocal reduction in sediment loss occurred by straw mulch, which mitigated the erosive effect of increasing rainfall intensities, even at the steepest slope. Furthermore, the conservation effectiveness during high rainfall intensities (94 and 120 mm·h^{-1}) increased with slope steepness (Figure 4b). Indeed, sediment losses during intense rainfall increased with slope steepness in un-mulched treatments, but with little effect of slope in mulch treatments (Table 3). Detached particles are transported by the flow velocity of runoff due to the slope effect [54]. The mulch reduced the overland flow and sediment losses by 52% and 93%, respectively, relative to the un-mulched treatment [55]. Moreover, the sediment loss could be reduced by up to 89% due to the mulch effect [56].

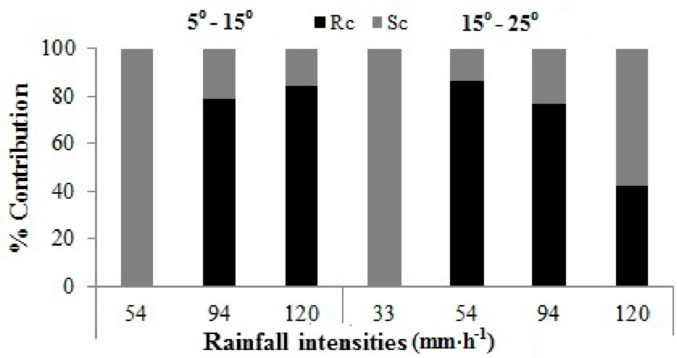

Figure 6. Rainfall (Rc) and slope (Sc) contributions for sediment losses under different rainfall intensities with increasing slope steepness from 5° to 15° and 15° to 25° in mulched Purple soil.

3.3. Water Infiltration

Water infiltration was calculated by subtracting the runoff losses from that of the total applied rainfall [57]. It was significantly influenced by rainfall intensity and slope in mulched and un-mulched treatments (Table 3). Infiltration rate decreased significantly (α = 0.05) with increasing slope level and increased with rainfall intensity both in mulched and un-mulched treatments (Table 3). Soil under mulch maintained a high infiltration capacity compared to that of the un-mulched soil. The maximum infiltration of 70.9 mm·m^{-2} was observed during rainfall of 94 mm·h^{-1} at the 5° slope in un-mulched treatments. While, the maximum infiltration rate of 112.7 mm·m^{-2} was recorded for rainfall intensity of 120 mm·h^{-1} at the 5° slope for the mulched soil.

Slope steepness is a key control of water infiltration into soil [58]. It influences surface storage capacity and pressure head during ponding; both of them decrease with an increase in slope [59] and are also affected by the raindrop density per unit of surface area [60]. Several experiments have been conducted to determine the influence of slope on water infiltration, but with conflicting results reported in the literature. Some have reported a positive impact of increase in slope on the infiltration rate [61,62]. However, the variations in slope may not strongly affect the infiltration rate and surface flow in the absence of erosion and a sealing soil layer [61]. The data for the un-mulched treatment indicate that slope had a negative effect on infiltration rate, probably due to the formation of surface sealing and an increase in rill formation on the steeper slopes (Table 3) [63–66].

The data presented in Table 3 indicate that slope is an important factor influencing the infiltration rate, but its effect differs with rainfall intensity in un-mulched treatments. A significant (α = 0.05) effect on the infiltration rate occurred with an increase in rainfall intensity from 33 to 54 mm$\cdot$h^{-1} at the lowest slope (5°), indicating that depression reserves are filled at lower slopes, thereby reducing the surface flow and increasing water infiltration capacity at higher rainfall intensities [35]. However, water storage ability of surface soil decreased with increasing slope steepness, thus, any increase in rainfall intensity and slope steepness could have resulted in decreased water storage ability, hence the non-significant change observed at the steepest slope (25°) between rainfall intensities of 33 mm$\cdot$h^{-1} and 54 mm$\cdot$h^{-1} (Table 3). Similarly, a further increase in rainfall intensity up to 94 mm$\cdot$h^{-1} caused a significant (α = 0.05) increase in the infiltration rate compared with that at a lower rainfall intensity and at a lower slope. However, at higher slopes, the infiltration rate was slightly reduced compared to that for the rainfall intensity of 54 mm$\cdot$h^{-1}. For the 5° slope level, occurrence of a higher ponding head pressure, due to the thick surface flow layer [10], may be the reason for the higher infiltration rate. However, at steeper slopes, high flow velocity increased the loss of water runoff, decreased the hydraulic gradient and reduced the infiltration rate during rainfall intensity of 94 mm$\cdot$h^{-1} [67,68]. Similarly, comparatively lower flow velocities during rainfall intensity of 54 mm$\cdot$h^{-1} could have promoted the maximum water absorption, thus, higher water infiltration occurred compared with that under the rainfall intensity of 94 mm$\cdot$h^{-1}.

The relationship between the infiltration rate and rainfall intensity has been widely reported [69–72]. The infiltration rate is negatively correlated with rainfall intensity in soils which are prone to surface sealing [73]. However, the infiltration rate increases with an increase in rainfall intensity on soils which do not form seals for two reasons: (1) the high spatial heterogeneity in the infiltration characteristics of the soil surface increases infiltration with an increase in rainfall intensity; (2) the increase in inundation of a progressively larger fraction of the micro relief, due to the increase in the runoff rate and flow depth. The data in Table 3 show that these mechanisms depend on the interaction of rainfall intensity with slope steepness. In un-mulched treatments at the 5° slope, cumulative infiltration of 70.9 mm$\cdot$m^{-2} during 94 mm$\cdot$h^{-1} rainfall intensity was 4.8% higher than the infiltration of 67.6 mm$\cdot$m^{-2} for rainfall simulations of 120 mm$\cdot$h^{-1}. However, at steeper slopes, the infiltration increased significantly (α = 0.05) during rainfall intensity of 120 mm$\cdot$h^{-1} (Table 3). These results indicate that, though the water ponding pressure could be high during the highest rainfall intensity, the faster wetting rate in drier soil under the rainfall event causes severe aggregate slaking and the attendant surface sealing. Furthermore, the soil at the gentle slope has a smoother surface because of an erosion crust [74]. Higher rainfall intensities not only supply more direct rainfall water but also generate more runoff water and increase the flow depth, which can dissipate the energy of the raindrop, protect the seal from breakage and decrease infiltrability [75]. The hydraulic conductivity of the surface seal is typically much lower than that of the underlying soil layer, which limits water infiltrating capacity [73]. Moreover, an increase in soil water content decreases the hydraulic gradient, thus reducing the driving force responsible for water infiltration into the soil. Therefore, a shallower water layer during a rainfall intensity of 94 mm$\cdot$h^{-1}, and the detaching effect of the raindrop was much higher than that for the rainfall intensity of 120 mm$\cdot$h^{-1}. The creation of a rougher micro-relief increased the surface area for infiltration, thus resulting in a slightly higher infiltration rate as compared with the rainfall intensity of 120 mm·h^{-1}. However, a significant increase during the highest rainfall intensity at 15° and 25° slopes could be due to the following reasons, (1) shallow flow depth and creation of a rough micro-relief [74]; and (2) reduced sealing because of an acute angle and less kinetic energy per unit surface area of the impacting raindrops at steeper slopes [62]. Thus, water infiltration increased with an increasing supply of water at higher intensities in un-mulched soil. However, infiltration was significantly increased with an increase in rainfall intensity up to 120 mm·h^{-1} in mulched treatments at all slope levels. Mulch cover protected the soil surface from raindrop impact [15] and consequently improved the water infiltration capacity (Table 3). Further, mulch cover also protected aggregate structure, prevented the seal formation [52] and reduced the water runoff, thereby increasing the infiltration rate with an increasing rainfall intensity for all slopes. As a result, the rainfall impact, as controlled by the rainfall intensity and slope steepness in this study, may have changed the infiltration rate with a change in rainfall intensities in un-mulched soil. However, mulch cover protected the surface soil from the striking effect of raindrops and absorbed the kinetic energy of rainfall, thus minimizing spatial variability of the surface soil, and creating similar micro-relief features during all rainfall intensities which increase the infiltration capacity with an increasing rainfall intensity in mulched treatments. In a previous experiment with 9 Mg/ha of bean straw in northeast Brazil, with controlled micro sprinkler irrigation depths, mulch efficiently retained soil moisture and reduced spatial variability [76]. It has been documented that the infiltration rate is a function of the accumulated rainfall depth and is significantly affected by the impact of raindrops [72]. Thus, mulched soils have a higher infiltration capacity compared with that of the un-mulched soil [77].

3.4. Recharge Coefficient

The recharge coefficient (RC) indicates the ratio of the total applied rainfall that infiltrated into soil and it is a measure of the efficiency of rainfall-infiltration [78]. The data (Figure 7) show the RC for all un-mulched and mulched treatments along with the mean values for various rainfall intensities and slope levels. In general, RC was lower for un-mulched compared with the mulched soil, ranging between 35.6% for rainfall intensity of 94 mm·h^{-1} to 99.5% for 33 mm·h^{-1}, at 25° and 5° slopes, respectively. In mulched treatments, relatively more runoff lag time resulted in higher RC (Figure 7b). With the use of mulch for lower rainfall intensities at all slopes, RC values were >90% and similar for rainfall intensities of 94 and 120 mm·h^{-1} at the 5° slope. However, any further increase in slope steepness decreased RC and the minimum value of 51.3% was recorded for rainfall intensity of 120 mm·h^{-1} at the 25° slope. Regression analyses of these variables were conducted to establish an empirical relationship between the RC and the three factors shown in Equation (3).

$$RC = 1.027 - 0.044RI - 0.011S + 0.171M \tag{3}$$

where RC, RI, S and M represent the recharge coefficient (%), rainfall intensity (mm·h^{-1}), slope (°) and mulch, respectively.

The high correlation coefficient ($r = 0.83$, $p < 0.001$), indicates that it has a high predictive capability (Table 4). Moreover, all regression coefficients were statistically significant (Table 5).

Table 4. Variance data for fitting Equation (3).

Source	DF	SS	MS	F	*p*
Regression	3	2.626	0.875	106.95	0.000
Residual	68	0.557	0.008		
Total	71	3.248			

Notes: DF = degree of freedom, SS = sum of square, MS = mean sum square.

Table 5. Regression coefficient tests for fitting Equation (3).

Variables	Coefficient	Std. Error	T	p
Constant	1.027	0.046	22.51	<0.000
RI	−0.044	0.003	−13.86	<0.000
S	−0.011	0.001	−8.11	<0.000
M	0.171	0.022	7.94	<0.000

Notes: RI = rainfall intensity (mm·h^{-1}), S = slope (°), M = Mulch.

Equation (3) indicates that the RC decreases with an increase in rainfall intensity and slope steepness, and increases with mulch application. A comparison of the absolute values of RCs in Equation (3) suggests that its most important determinant is mulch cover, followed by the rainfall intensity and the slope. The importance of these factors for water infiltration into soils has already been reported [79]. Increasing the rainfall intensity would slake and disrupt the structure of the top soil and form surface seals [73,80–82], which reduces hydraulic conductivity [71]. In this study, though the water infiltration rate increased with an increase in rainfall intensity (Table 3), a fast wetting during rainfall events of higher intensity could have reduced the water recharge in soil and the above trends might be attributed to the differences in infiltration rates caused by the wetting rates. A more rapid decline in the hydraulic gradient under the intense rainfall events is a factor reducing the infiltrability observed between the storms of lower and higher intensities [67]. Furthermore, higher rainfall at steeper slopes caused higher flow velocities leading to less opportunity for water transmission into soil layers and the magnitude of surface runoff, and the recharge of soil are directly affected by the amount of water infiltrating the soil surface [75]. Therefore, greater rainfall intensities might reduce soil water recharge and increase surface flow [83]. However, retardation in runoff and lower flow velocities under mulched conditions provided longer time for the water to be in contact with the soil surface, thus enhancing the water transmission into the soil for the same slope levels and rainfall intensities (Figure 7). With reference to simulated experiments, previous researchers reported that mulch cover dispersed the large raindrops into small raindrops, which reduced the actual rainfall intensity on the ground and made the rainfall intensity less than the infiltration capacity; as a result the infiltration rate increased with rainfall intensity from 0 to 176 mm·h^{-1} [84].

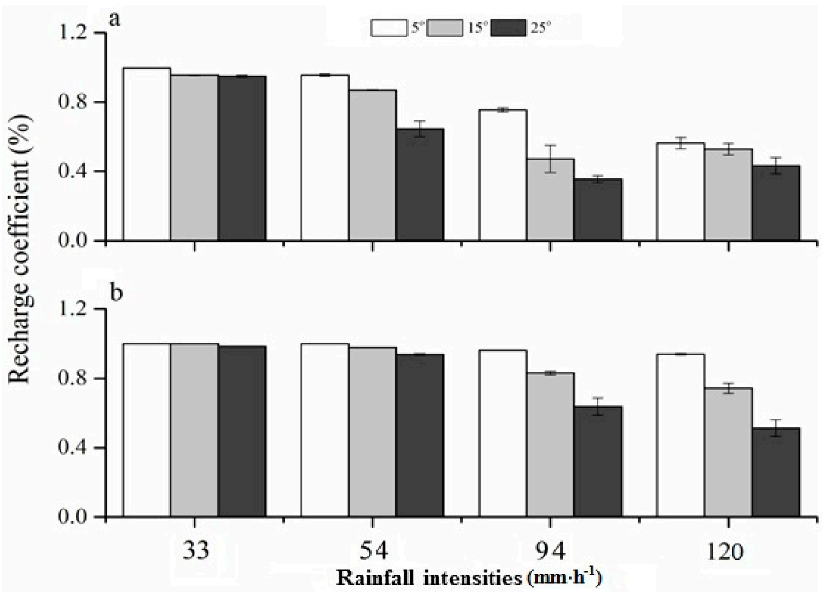

Figure 7. Effect of treatments on the recharge coefficient in (**a**) un-mulched and (**b**) mulched soil.

4. Conclusions

The data presented support the following conclusions:

1. In un-mulched treatments for all rainfall intensities, slope was the dominant factor in sediment loss, while the runoff process was independent of slope steepness for rainfall of high intensities.
2. In mulched soil, the contribution of rainfall intensity was >50% in producing sediment loss, and controlled by the wash flow under mulch cover. However, the mulch cover reduced the flow rate, and the slope steepness controlled the magnitude of water runoff.
3. Straw mulch significantly reduced sediment and water losses. Under high rainfall intensity, the conservation effectiveness of mulch increased with increasing slope steepness. On the contrary, the magnitude of reduction in water loss decreased with an increase in slope steepness at higher rainfall intensities.
4. The infiltration rate decreased with an increase in slope and increased with an increase in rainfall intensity. The effect of rainfall intensity on the infiltration rate changed with the slope angle due to the creation of different micro-relief features. In mulched soil, however, the water infiltration rate significantly increased with an increase in rainfall intensity at all slopes because of the uniform surface conditions under the mulch layers. The recharge coefficient decreased with an increase in rainfall intensity and an increase in slope steepness in all treatments, whereas the mulch maintained a higher infiltration rate and RC compared with un-mulched treatments.
5. The short slope length in this experimental setup resulted in less surface area availability for water recharge into the soil during intense rainfalls. Due to a smaller quantity of runoff and lower velocities during low rainfall intensity, the slope effect could be generalized to field conditions. However, for intense rainfalls, the slope effect could be different under field conditions in that; the steeper and the longer slopes would have a higher infiltration rate with increasing rainfall intensities because of the availability of a large area for water infiltration with increasing slope length. Therefore, additional field research is needed to study the effects of longer and steeper slopes on the water infiltration rate and runoff loss under intense rain storms.

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