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Seyed Hamidreza Sadeghi, Zeinab Hazbavi, Mahboobeh Kiani-Harchegani, Habibollah Younesi, Padidehsadat Sadeghi, Rafaël Angulo-Jaramillo, Laurent Lassabatère

How Hydrologic Behavior of Loess and Marl Soils Responds to Biochar and Polyacrylamide Mulching under Laboratorial Rainfall Simulation?

Seyed Hamidreza Sadeghi[1,*], Zeinab Hazbavi[2], Mahboobeh Kiani-Harchegani[3], Habibollah Younesi[4], Padidehsadat Sadeghi[5], Rafael Angulo-Jaramillo[6] and Laurent Lassabatere[7]

[1,*] Professor (Corresponding Author), Department of Watershed Management Engineering, Faculty of Natural Resources, Tarbiat Modares University, Noor 46417-76489, Iran. E-mail: sadeghi@modares.ac.ir

[2] Assistant Professor, Faculty of Agriculture and Natural Resources, Member of Water Management Research Center, University of Mohaghegh Ardabili, Ardabil, Iran. E-mail: z.hazbavi@uma.ac.ir

[3] Postdoctoral Researcher, Department of Watershed Management Engineering, Faculty of Natural Resources, Yazd University, Iran. E-mail: mahboobeh.kiyani20@gmail.com

[4] Professor, Department of Environment, Faculty of Natural Resources, Tarbiat Modares University, Noor 46417-76489, Iran. E-mail: hunesi@modares.ac.ir

[5] M.Sc. Student, Department of Watershed Management Engineering, Faculty of Natural Resources, Tarbiat Modares University, Noor 46417-76489, Iran. E-mail: Pssadeghi1371@gmail.com

[6] Chargé de Recherche CNRS, Université de Lyon; UMR5023 Ecologie des Hydrosystèmes Naturels et Anthropisés, CNRS, ENTPE, Université Lyon 1, Vaulx-en-Velin, France. E-mail: angulo@entpe.fr

[7] Research, Université de Lyon; UMR5023 Ecologie des Hydrosystèmes Naturels et Anthropisés, CNRS, ENTPE, Université Lyon 1, Vaulx-en-Velin, France. E-mail: Laurent.LASSABATERE@entpe.fr

Abstract

Due to the high costs of soil erosion control actions, the precise selection of practical techniques is requisite for a sustainable land management. To proper application of anti-erosion measures, a good knowledge from the behavior of the soil erosional and hydrological properties is required. Many researchers indicated that biochar (BC) and polyacrylamide (PAM) are important soil amendments to enhance soil physical and hydrological characteristics. However, little is known about the response and mechanisms of two prone-erosion soils of Marl and Loess against the individual and combination of the BC and PAM applications. Therefore, the present study was planned to test the effectiveness of these anti-erosive techniques on variability of 1) hydrological components (i.e., time to runoff, runoff coefficient and infiltration); 2) runoff quality components (i.e., pH and electrical conductivity, EC) and 3) erosion components (i.e., upward-splash, downward-splash and net-splash erosion, soil loss and sediment concentration) at two soils of Marl and Loess under rainfall simulation conditions. The study treatments were consisted of control (200 ml water), BC (800 g m^{-2}), PAM (2 g m^{-2}), and BC (800 g m^{-2}) + PAM (2 g m^{-2}). The treatments were sprayed uniformly over the small plots (0.3 × 0.5 × 0.5 m in dimensions; 0.25 m^2 in area) with slope of 20% in three replicates. The rainfall with an intensity of 50 mm h^{-1} and duration of 0.5 h was applied. The results showed that **a)** only PAM delayed the time to runoff with rate of 41.4% compared to control treatment at Marl soil and all treatments delayed the time to runoff of Loess soil (BC=37.1% and PAM=BC+PAM=12.9%); **b)** among the study treatments, PAM had the greatest effect due to decreasing runoff coefficient by 2.47 and 13.67%, and improving infiltration by 0.02 and 0.13% at Marl and Loess soils, respectively; **c)** BC and BC+PAM increased the pH values of runoff whilst the PAM applications partially reduced the pH compared to the control plot at both study soils; **d)** the BC and BC+PAM applications significantly (P<0.05) increased EC of runoff released from both tested soils. In contrary, PAM had the least influence on EC of the runoff in comparison with the control condition; **e)** the maximum effect on soil loss reduction was attributed to BC for Marl and Loess soils respectively with rates of -14.07 and -83.21%. In addition, the maximum benefit on sediment concentration reduction was attributed to PAM (-14.87%) and BC (-78.35%) respectively at Marl and Loess soils; **f)** all treatments reduced the upward-splash, downward-splash and net-splash erosion at both study soils in range of -13.69% (BC+PAM at Loess soil) to -73.68% (BC at Marl soil) in comparison with control.

Keywords: Erosion flux; Hydrologic response; Pyrogenic carbon; Runoff mitigation, Soil management

1. Introduction

Soil erosion is an important process of terrestrial degradation in many parts of the world (Pereyra et al., 2020; Zaimes et al., 2020). It also lead to exacerbate poverty and food insecurity in the densely populated areas. Since, it affects not only the soil resources but also has influence on the water, vegetation, landscape, and microclimatic components of ecosystems (Hazbavi et al., 2019; Scholten and Seitz, 2019; Wüpper et al., 2019). New management and techniques are recently introduced to reduce soil erosion and to achieve goals related to land sustainability. Natural or synthetic soil amendments as non-structural best management practices (BMPs) are used to sustain appropriate soil and water resources properties (e.g., Ekebafe et al., 2015; Liu et al., 2018; Ul Zaman et al., 2018). Application of proper soil amendments for soil erosion control and water conservation has become an increasingly common option to improve the land sustainability (e.g., Sadeghi et al., 2014; Behzadfar et al., 2017; Alkhasha et al., 2018). The literature highlighted that the addition of pyrogenic organic matter (biochar; BC) and polymers resulted in a plethora of predominantly reduction in the soil erosion and its components including runoff, soil loss and sediment yield (e.g., Hazbavi et al., 2012; Soo et al., 2015; Sadeghi et al., 2016a, b and c; Kianian et al., 2018; Yakupoglu et al., 2019; Ao et al., 2019; Wang et al., 2019; Li et al., 2019; Villagra-Mendoza and Horn, 2019; Sanford and Larson, 2020). The use of BC produced from biomass waste is introduced as a sustainable solution for waste disposal in viewpoints of environmental, ecological and economical aspects (Ghezzehei et al., 2014). Besides, polyacrylamide (PAM) is produced into a long-chain synthetic polymer and is as a strengthening agent to soils in place against soil erosion (Soltani-Jigheh et al., 2019).

BC and PAM addition to soils could change the soil hydrology process through changes in the water holding capacity, water infiltration, runoff generation, soil drainage, soil water repellency, soil penetration resistance, and water delivery to plants (e.g., Dorraj et al., 2010; Wang et al., 2011; Kinney et al., 2012; Wei et al., 2014; Zong et al., 2016; Sadeghi et al., 2016a, b and c; Sandhu and Kumar, 2017). The effects of PAM and BC treatments in changing soil erosional and hydrological behaviors were mostly related to increasing clay flocculation, soil aggregation process and aggregate sizes (Hseu et al., 2014; Bayabil et al., 2015; Lee et al., 2015; Yakupoglu et al., 2019). Because different factors affecting the BC and PAM efficiency in the improving soil erosional and hydrological properties, various results were found in different regions of the world. A variety of characteristic in terms of climatic, especially in terms of rainfall variables (e.g., intensity, duration, frequency), edaphic (e.g., soil texture, soil structure, particle size distribution) and soil hydraulic (e.g., bulk density, saturated hydraulic conductivity) could be specified as determinant factors. Besides, the initial characteristics of BC and PAM treatments have been considered as potential source of change in their effectiveness on improving erosion and hydrological properties in terms of quantity and quality. For example, the type of raw material used to BC production is very critical. Sun et al. (2017) characterized 60 types of Chinese biomass waste and highlighted the resultant BC in terms of their candidacy for soil application. Their results verified the different effect of biomass pyrolysis on the BC efficiency. The physical and chemical properties of BC and PAM and the method of their application need to be further considered as well. In this regard, Li et al. (2019) demonstrated that the different BC particle size and time of incubation changes the time to runoff initiation, runoff volume and erosion rate.

The quality of runoff generated from treated soil is also critical for river engineers and ecologists. It is high important to provide information on the soil amendment effects on the runoff quality especially in terms of pH and electrical conductivity (EC). PH and EC are key factors regulating the ions concentration in the soil solution. There are also relationship between pH and EC increasing, soil dispersal and infiltration decline (Butnan et al., 2015; Lee et al., 2015). Hence, it is better to monitor the pH and EC values of runoff generated from soils treated with BC and PAM.

Previous studies suggest that both individual and combined application of BC and PAM have both short and long terms effects on soil erosion mitigation and hydrology process after application, ranging from a few days to several months or years. For example, Hseu et al. (2014) studied the impacts of BC made from rice hull biochar at rates of 2.5, 5, and 10% (w/w) on soil physical and erosion properties of a Mudstone slope land under incubation experiment (disturbed soil). Their findings only proved the positive effect of 10% BC on the water conductivity that leading a substantial macropores increasing and soil strength decreasing. The simulation results also showed the significant reduction (i.e., 35 to 90%) of soil loss after BC application. Sandhu and Kumar (2017) evaluated the impact of three plant-based BC materials (ponderosa pine, corn stover, switchgrass and wood residue); dairy manure; and manure+pinewood BC on the hydrological properties (i.e., soil water infiltration rate, soil water retention, and pore size distribution) of undisturbed soils. According to the experiment findings, the significant effect of BC and manure applications on soil hydrological behaviors especially a negative effect on soil penetration resistance was obtained. Lee et al. (2018) investigated the effectability of erosion components from applications of wood BC+green waste dreg compost, and PAM for an undisturbed tropical soil. The higher effectiveness of BC than PAM was reported for runoff control and infiltration improvements. In the same vein, Ao et al. (2019) explored the high positive impact of PAM application, at an optimal rate of 2 g m^{-2}, on reducing runoff and soil splashing for the Kastanozem soil using indoor rainfall simulation. They reported that the PAM amendment highly controlled runoff and sediment amounts as well as ammonia and nitrate loss. Li et al. (2019) also investigated the effects of BC with various particle sizes on water erosion processes of cultivated Loess soil under laboratory experiments. They concluded that the total runoff volume and total erosion after BC additions with different particle sizes decreased up to some 31% with slight difference under no- and eight months-incubations. They reported the effectiveness of BC for soil conservation due to increasing of water-stable soil aggregates and saturated hydraulic conductivity (k_{sat}). Further, Peng et al. (2019) evaluated the impacts of BC on interrill erosion developments for an undisturbed silt loam soil. They showed that BC improved the soil aggregate stability and ultimately reduced the interrill erosion potential at a maximum rate of 21.34%. Whilst, the BC could not affect runoff generation in comparison with that of control soil. Villagra-Mendoza and Horn (2019) determined the impact of wetting and drying conditions on the infiltration behavior of two BC amendments and to validate the performance of infiltration models. They found that the BC addition decreased infiltration due to the formation of narrower pores led to reduced infiltration capacity. The higher the BC dosage, the more resilient the treatment became concerning the changes on the water infiltration. Wang et al. (2019) studied the synergic influences of BC and PAM for coastal soil restoration in China. The soil cohesion was decreased due to BC application and considerably increased in result of PAM treatment. It was concluded that application of BC and PAM together improved the quality and stability of study undisturbed silt loam soil. Yakupoglu et al. (2019) also applied PAM to measure its effect on the time to runoff, total runoff, sediment yield, and splash sediment yield at laboratory erosion plots. The results showed that PAM did not delay runoff initiation; however, it reduced the total runoff, sediment yield, and soil transported by the splash. In addition, Zhang et al. (2019) examined the effects of BC additions pyrolized from hickory hardwoods and seasoned oak to control runoff, and interrill erodibility of Loess-derived Miami soil, China. The BC treatment decreased the total runoff by 2.4–10.8% ($p>0.05$) and increased the interrill erodibility by 20.4–29.2% ($p<0.05$) under disturbed conditions. The high risk of BC for erosion intensification of sloping croplands was emphasized. Recently, the applicability of individual and combined application of vinasse-BC and PAM was evaluated by Sadeghi et al. (2020) under semi-real conditions (rainfall simulation on undisturbed soil in the field). Accordingly, the effective reduction in soil loss in Marl and Loess soils by PAM was reported. They also verified that BC differently affected runoff and soil loss control in Marl and Loess soils.

As it could be understood from the literature reviewed, in overall, the different results for various environmental conditions for both disturbed and undisturbed soils were observed. Both positive and negative effects of BC and PAM were attributed to various components of soil hydrology and erosion processes. In addition, how individual and combined BC and PAM application affect the hydro-erosional process have not been cleared for erosion-prone soils of Marl and Loess. Therefore, it is important to test the potential BC and PAM application in the laboratory to understand the different performances of study amendments for runoff and soil loss control in soils, which are intrinsically sensitive to water and soil losses. On the other hand, the executive managers of Iran are not sure to use the preventative approaches or remedial techniques for soil and water resources management in areas underlain by sensitive formations. Towards this, there is a particular need to collect more data on the hydrological impacts of various amendments under laboratory experiments before their field application. It, obviously, facilitates appropriate investment on proper amendments leading to economically efficient and environmentally sound improvement of the land resources.

Besides the necessity of fulfilling existing gaps mentioned above, a comprehensive study is crucial to simultaneously evaluate the effect of individual and combined application of BC and PAM to Marl and Loess soils seriously sensitive to soil erosion. Marl soils have physical properties such as constructional nature and high deposits of silt and low clay. These soils also characterized by calcium carbonate, gypsum, anhydrite and salt. Thus, they are high erodible and limited in terms of vegetation (Sharifi, 2016). Marl formation is regarded as one of the most sensitive geological formations against erosion and weathering having a major role in the sediment yield at the watershed scale in Iran (Vaezi and Gharehdaghlii, 2013; Sharifi, 2018; Sharifi and Shamirzadi, 2018; Zobiri et al., 2018). Due to the lack of vegetation, the erosion process in Marl reduces permeability, as a result, various types of progressive erosion can be clearly seen in Marl areas (Tamartash et al., 2010). In addition, the Loess soil, as the most widespread deposit of the Aeolian dust on the globe, often contains little clay resulting in a loss of soil organic carbon (SOC) under cultivation (Catt, 2001; Ajami et al., 2016; Maleki et al., 2018). Their particle size distribution consists of mostly silt that results in high rate of soil erosion (Isaie and Soufi, 2008). Furthermore, the uppermost part of the Loess soils is built without any pedogenetic features (Vlaminck et al., 2018). Loess soils are therefore erosion sensitive (Lu et al., 2018; Maleki et al., 2018). Broad parts of the northern slopes of the Alborz Mountain Range in northern Iran particularly in Maravehtapeh Region, Golestan Province, are protected by large volume of Loess deposits (Khormali and Kehl, 2011). The area is heavily being deforested and also cultivated (Ajami et al., 2016) leading to severe gully erosion (Soufi and Isaie, 2007).

Although many research on the soil erosion assessment and hydrological process investigation have been conducted for Marl and Loess soils (Zobiri et al., 2018), knowledge on their controllability is still incomplete and there are considerable uncertainties, particularly with regard to the effectiveness of anti-erosion techniques in the Marl and Loess areas. Therefore, any conservation activity in order to control the soil erosion in Marl and Loess soils is of particular importance and has an acceptable economic justification (Sharifi, 2018; Sharifi and Shamirzadi, 2018). In the previous studies (Hazbavi et al., 2016; Sadeghi et al., 2016a; Sadeghi et al. 2020), the significant effect of application of Vinasse-BC at rate of 8 t ha^{-1} for the runoff and erosion control for a sandy clay loam soil of northern Iran was proved. However, it was found that BC was being easily floated by the runoff water during rainfall events, which necessitates the amendment of an additive to improve the adherence. Sadeghi et al. (2020) recently applied BC and PAM individually and in combination to the small plot scales installed in field. Nonetheless, the field condition would not be expected fully controlled and therefore more control conditions were essentially needed to assess the comparative performance of the study amendments. According to the successful application of PAM in reducing runoff and soil erosion and its polymeric nature (i.e., linearly-linked, water-soluble acrylamide sodium acrylate copolymer, adhesive, easy to penetration), the present study was ultimately formulated with the aim to test the interactive effects of BC and PAM under laboratory simulation for two erosion-prone soils of Marl and Loess. The present study was conducted with the hypothesis that the application of combined BC and PAM to soil could improve the hydro-erosional variables of Marl and Loess soils more than their individual application as a result of the synergy effects caused by the presence of the higher number of pores and the higher surface area of BC compared with other amendments and adhesiveness nature of PAM. Towards this, the present study was planned to test the effectiveness of individual and combined application of BC and PAM on variability of 1) hydrological components (i.e., time to runoff, runoff coefficient and infiltration); 2) runoff quality components (i.e., pH and electrical conductivity, EC) and 3) and erosion components (i.e., upward-splash, downward-splash and net-splash erosion, soil loss and temporal variation of sediment yield) at two soils of Marl and Loess under rainfall simulation conditions.

2. Materials and Methodology

The effectiveness of anti-erosion techniques for two different soils of Marl and Loess located in the northern Iran was characterized by application of BC, PAM and BC+PAM amendments. Fig. 1 illustrates an overview of the study methodology.

Fig. 1

2.1. Soils sampling and analyses

Surface samples (0–20 cm depth) of both study soils that usually spread in northern Iran, and made from various parent materials, were nominated. The soil parent materials of study areas were Marl and Loess, respectively collected from Marzanabad (51° 23.3620′ E and 36° 28.6520′ N; 568 m amsl; Mazandaran Province) and Maravetapeh (55° 26.1550′ E and 37° 35.9510′ N; 409.6 m amsl; Golestan Province), Iran (Fig. 2). The climates of Marzandabad and Maravehtapeh regions are semi-arid cold and semi-arid, respectively. The mean annual precipitation and temperature were respectively estimated about 432 mm and 12.0 °C for Marzanabad region, and in that respect were about 350 mm and 17.7 °C for Maravehtapeh region (Eteraf and Telvari, 2003; Amini Jahromi et al., 2008; Eteraf et al., 2014; Kheirfam et al., 2017).

The texture, pH, electrical conductivity (EC) and bulk density were respectively assessed silty clay loam, 7.68, 210 µS cm^{-1} and 1.12 g cm^{-3} for Marl soil; and in that respect were obtained loam silty, 8.20, 750 µS cm^{-1} and 1.13 g cm^{-3} for Loess soil (derivation methodology was similar to Eteraf and Telvari, 2003; Amini Jahromi et al., 2008; Eteraf et al., 2014; Kheirfam et al., 2017). The particle size distribution analysis demonstrated the 42% clay, 43% silt and 15% sand for Marl soil and 57% clay, 36% silt and 7% sand for Loess soil.

2.2. Study Treatments

Experimental treatments consisted of soil without amendments (i.e., control; 120 ml m^{-2} of tap water), BC powder (800 g m^{-2}), solute PAM (16.67 g l^{-1} m^{-2} dissolved in 120 ml of tap water), and combined application of BC+PAM (firstly 800 g m^{-2} of BC powder and over uniformly sprayed by 16.67 g l^{-1} m^{-2} of PAM). The soil amendment and used tap water values were selected according to previous experiences and preliminary experiments to soil erosion and runoff mitigation (Hazbavi et al., 2012, 2016; Sadeghi et al., 2016a, b and c). BC was produced through pyrolysis of solid vinasse provided from Sugarcane Development Company of Khuzestan Province, Iran, for 6 h in temperature of 450°C (Sadeghi et al., 2016a). The essential characteristics of the vinasse and vinasse-BC are indicated in Table 1.

Table 1

A granular anionic PAM, with a high molecular weight of 10–15 x 10^6 g mol^{-1}, was used for this research (Hazbavi et al., 2012; Sadeghi et al., 2016b). The overview on the study soils of Loess and Marl soils, PAM and BC are presented in Fig. 2.

Fig. 2

2.3. Experimental plots

In July 2019, experimental plots were set up in a completely randomized design to remove the effect of potential variable environmental conditions such as un-uniformity of rainfall intensity or weather temperature and humidity during the experimental days. The plots were 50×50 cm in size, with three replicates of each soil and each single amendments and combinations, plus an untreated control in each replicate (i.e., 2 soils × 4 treatments × 3 replicates = 24 plots). After washing and cleaning the plots, 17 cm of mineral pumice grains were used as a filter layer under the experimental soil. Then a sheet of porous jute was placed to separate the mineral pumice from the upper layers of soil. Afterwards, the air-dried and sifted soil passed through a 3.0-mm standard sieve was placed with depth of 10 cm at the top and over the filter layer and then compacted. To stabilize the soil mantle and introducing appropriate moisture to the soil, all study plots were saturated from the bottom for some 10 h with the help of big water containers. The saturated plots were then exposed to natural conditions for 48 h for free drainage and evaporation and getting antecedent moisture content of some 20% (Hazbavi and Sadeghi, 2016; Sadeghi et al., 2016a and b). The plots were established on an iron framework with a slope of 20% (i.e., 11.5°) similar to the mean slope of the soil origin. It is important to note that the small plots (<1 m2) have been the subject of criticism by several studies. Anyhow, it was decided to work with this plot scale since it is possible to subject to a standardized rainfall simulator have been well-specified and defined by our previous studies (e.g., Sadeghi et al., 2014; 2016a, b and c; 2018; 2020), considering the price and laboratory space limitations.

2.4. Rainfall simulation

Each erosion plot was subjected to design rainfall event (Eteraf and Telvari, 2003; Amini Jahromi et al., 2009; Shoemaker, 2009; Eteraf et al., 2014; Sadeghi et al., 2016a and b; Kheirfam et al., 2017) with intensity of some 50 mm h^{-1} and duration of 30 min. The rainfall was simulated from the height of about 4 m using two movable BEX 3/8 S24W nozzles with an adequate aperture area allowing working on three plots (with dimensions of 0.50×0.50 m), simultaneously. The mean terminal velocity and rain drop mean diameter created were about

7 m s^{-1} and 1.18 mm, respectively, similar to the specifications reported for rains occurred in northern Iran (Sadeghi et al., 2013). The calibration of rainfall simulation were entirely conducted under laboratory conditions at the Soil Erosion and Rainfall Simulation Laboratory of Tarbiat Modares University, Faculty of Natural Resources, Noor, Mazandaran Province, Iran. The mean intensity of the simulated rains was also checked during each experiment to ensure the similarities among study events. An overview of rainfall simulation apparatus is shown in Fig. 3.

2.5. Measurement of runoff and soil erosion components

The time to runoff was regarded as the elapsed times between the start of rainfall and the time at which surface runoff began entering the runoff collection container (Chow and Rees, 1995) at the lower end of the plot. It was recorded using a timer with an accuracy of 0.01 s. Runoff water laden with eroded materials were then sampled consequently every two min (for the first 6min of experiment after beginning of the runoff), 3 min (for the next 9min of the event) and finally 5 min (the last 15min of the event) throughout the each simulated rainfall (Hazbavi and Sadeghi, 2016). The runoff and soil loss amounts were measured with the help of a gauged cylinder and decantation procedure, respectively (Behzadfar et al., 2017). The runoff coefficient was calculated through dividing the runoff intensity (Eq. 1) to rainfall intensity (50 mm h^{-1}) (Hazbavi et al., 2016).

$$\text{Runoff intensity (mm h}^{-1}\text{)} = \text{runoff volume (mm}^3\text{)/(time interval (h)*area (mm}^2\text{))} \qquad (1)$$

The difference between rainfall and runoff was also considered as infiltration, since there was no seepage from the plots (Hazbavi and Sadeghi, 2016; Sadeghi et al., 2016 a and b). The splash erosion induced by raindrop impacts was also measured using one splash cup with outside diameter of 25 cm, height of 10 cm, and an inside diameter of 10 cm and an inner edge height of 2.5 cm, placed at the center of each experimental plot (Sadeghi et al., 2016c and 2018) as demonstrated in Fig. 3. The eroded soils during whole rainfall event collected at upper (i.e., upward-splash) and lower (downward-splash) parts of the splash cups, then oven dried for 24 h at 105 ºC and weighted. Finally, the subtracting splashed soils on upward and downward directions was considered as the net splash erosion (Sadeghi et al., 2016c and 2018). Additionally, the pH and electrical conductivity (EC) of runoff samples were determined using portable pH and EC meters.

Fig. 3

2.6. Data analyses

All hydrologic study variables for treated and control plots with three replications were banked and graphically pictured in Excel 2016 and associated descriptive statistics were calculated for each treatment and for both the study soils of Marl and Loess. In order to statistically compare means of hydrologic variables in the study treatments with those recorded for the control plots, the data normality and homogeneity of variances were initially tested using Kolmogrov–Smirnov and Levene tests, respectively (Razali and Wah, 2011; Sadeghi et al., 2018). The analysis of variance (ANOVA) test was also used to assess differences in mean measured variables between treated and control conditions and for both the study soils. All statistical analyses were performed using IBM SPSS Statistics 25.

3. Results and discussion

3.1. Runoff components

The main results of study runoff components and their statistical analysis are presented in the Table 2.

Table 2

3.1.1. Time to runoff

Under the study conditions, time to runoff ranged from 103.33 s to 225 s depending upon the soil properties and treatments (Table 2). The maximum increase in time to runoff for Marl and Loess soils was 14.41 and 37.10% respectively under PAM and BC treatments compared to control (Fig. 4). The experiments for Marl soil showed that BC and BC+PAM respectively decreased the time to runoff by 22.03 and 36.61% (P>0.05), while PAM increased the time to runoff at a tune of 14.41% (P>0.05). The mean change of BC, PAM and BC+PAM effectiveness in time to runoff of Loess soil were found with rate of +37.10, +12.90 and +12.90%, respectively (Fig. 4). The results indicated that treated soils of Marl and Loess did not cause a significant (P>0.05) increase in time to runoff compared to the control (Table 2). The general trends were observed for effect of treatments on the time to runoff from maximum to minimum for the Marl soil was as BC>Control>PAM>BC+PAM and by instead of for the Loess soil was as PAM>BC=BC+PAM>Control.

For our study, it could be concluded that the ineffectiveness of BC and BC+PAM in delaying the time to runoff at Marl soil is related to the physical, chemical, and mineralogical properties of this soil. It also supposed that the plot scale (0.25 m^2) and the short time between soil amendment application and rainfall simulation (48 h) might be affected our results. To verify the obtained results, it is suggested to use larger plots and longer span time in the future research. It is also hypothesized that a longer time of BC application before the rainfall event (e.g., more than one week) will help complete the interactions between the soil and amendments in the Marl soil with a silty clay loam. Our observation also verified that the fresh BC was hydrophobic. In addition, the high viscosity that caused by study amendments is another reason to their low- or ineffectiveness in delaying time to runoff. On the other hand, the longer time to runoff in the study treatments for Loess soil could be related to lack of clay, which facilitates better interaction between BC and PAM with the soil particles. In this line, Yakupoglu et al. (2019) showed that PAM did not significantly (P>0.05) delay the runoff generation in comparison to the control treatment for different soil aggregate sizes and sequential rainfall events in Turkey. They conclude that the PAM could penetrate to the aggregate soils and improve the structure. However, antecedent soil moisture was reported as a potential factor that could modify the soil aggregate stability. So that, the activation of the runoff and soil loss after the sequential rainfall was higher than after the first rainfall.

Similar to our results, Marete et al. (2013) showed that the addition of PAM to the clay loam soil neither reduced the total runoff or time to runoff initiation significantly during the first rainfall application nor for the subsequent three rainfall applications. Whilst, Sadeghi et al. (2016a) reported the significant (p=0.014) effect of BC amendment in increasing the time to runoff compared with untreated plots under lab experiments for a sandy clay loam soil collected from rangelands of the Alborz Mountains, northern Iran. The rates of +71.73% and +55.10% of mean change in time to runoff were found respectively for BC application at 48 and 24 h before the simulation treatment compared with that reported for control condition. These different hydrological reposes is related to the soil physical protection provided by BC against crusting and consequently infiltration increasing. In addition, Peng et al. (2019) reported the effective role of BC on delaying the time to runoff generated from a silt loam soil particularly when applied at a higher rate (i.e., 30 t ha^{-1}). They concluded that the saturated hydraulic conductivity (k_{sat}) of soil is one of the main factors affecting the time to runoff generation. Towards to un-similar results obtained by BC for different conditions, Olsson et al. (2019) and Sadeghi et al. (2020) also concluded that BC is a land management technique of high potential, but controversial. Sadeghi et al. (2020) related the reduction in the time to runoff generation to the physical adhesion of the soil surface, the salts existent, and nature of the material that protected the Marl and Loess soil mass.

3.1.2. Runoff coefficient

The results presented in Fig. 4 showed that BC had increasing effect on runoff coefficient for both Marl (29.18%) and Loess (5.11%) soils. While, the changes in runoff coefficient were as -2.47 and -13.67% for Marl and Loess soils for PAM treatment. The combined BC and PAM treatment also increased the runoff coefficient from 38.66 (control) to 47.29% for Marl soil and from 46.42 (control) to 54.70% for Loess soil. The minimum runoff coefficient appeared in PAM application for Marl and Loess as 37.70 and 40.07%, respectively. The obtained trend for runoff coefficient was observed as PAM<Control<BC+PAM<BC for Marl soil and as PAM<Control<BC<BC+PAM for Loess soil. Similar to the time to runoff results, here is also the higher efficacy of PAM rather than BC and BC+PAM treatments was attested. Then, it is expected to follow similar mechanisms. While, it is hypothesized that the addition of BC to soil especially in combination with PAM due to its alkaline nature caused a viscosity on the sensitive soil surfaces of Marl and Loess and intensified the runoff coefficient. The effectiveness of PAM and ineffectiveness of other two treatments compared to control plots in decreasing runoff coefficient could be dependent on the soil physic and chemistry. Both study soils suffer from existing high amount of silt and some chemical materials that are anti-aggregations (Catt, 2001; Soufi and Isaie, 2007; Ajami et al., 2016; Maleki et al., 2018). In addition, the constant conditions of rainfall intensity, time span between treatment application and simulation, plot scale and method of treatment application could be considered as limiting factors. For example, it is supposed that if the treatment will be mixed with the top surface soils, better results will be obtained. This could be examined by future research.

The present finding is consistent with Hazbavi et al. (2012), Sadeghi et al. (2016b) and Sadeghi et al. (2020) who reported the positive effects of PAM application on runoff components. Some studies, with contradictory results, have investigated the effect of BC and PAM on the runoff coefficient of amended soils. Khademalrasoul et al. (2014), Hazbavi et al.

(2016) and Farhoodi et al. (2019) reported positive effects of BC on runoff coefficient respectively for arable sandy loam, loam clay sandy and clay soils of Iran. Despite BC potential to reduce runoff coefficient for some cases and its widespread land application, the uncertainties outlined on its negative effect on runoff coefficient under Marl and Loess soils of northern Iran is a serious concern. It is assumed that the properties of BC strongly depend on the raw materials, the conditions of production, soil properties and climatic characterizations. Wei et al. (2014) stated that the PAM application with rates of 0.5, 1.0, and 2.0 g m^{-2} increased the runoff coefficient as compared with control treatment of Loess soils in China.

No significant difference ($P>0.05$) in runoff coefficient was found between treatments. In addition, hydrophobicity (water repellency) was observed in all amended soils (visual interpretation). This is possibly due to clogging soil pore by viscous PAM solution application that has also been reported by Lee et al. (2015) who reported that BC, PAM and BC+PAM increased runoff compared to the control. Lee et al. (2018) further reported the stronger floating and hydrophobicity of BC compared to that of soil particulates. They reported slightly increase in the hydrophobicity of the sandy loam soil-BC mixture.

The results also showed that the conservation treatments had no significant effect ($P>0.05$) on runoff coefficient changes compared to the control treatment. Besides, the reductions of mean soil pore size from 0.07 to 0.046 mm^2 and soil tensile strength from 466 to 164 kPa due to BC application (5% w/w) were recorded by Devereux et al. (2012) and Zong et al. (2016). In addition, Lee et al. (2015) attributed the increased runoff from loam soils subjected to BC, PAM and BC+PAM amendments to clogging soil pore. Studies showed that the addition of PAM to the clay loam soil did not reduce the total runoff significantly under different conditions (Vacher et al., 2003; Marete et al., 2013). Wang et al. (2011) also noted that the 2 g m^{-2} PAM application increased runoff as compared to the control. The same results were obtained by Lee et al. (2015) who found that the runoff increased by 14.8, 22.9, and 23.2%, respectively in the plots amended with BC, PAM, and BC+PAM, compared to the control. They concluded that the increases of runoff were mainly resulted from PAM addition.

3.1.3. Infiltration

As seen in the results the amount of the water infiltrated to the soil with no significant difference ($P>0.05$) ranked from the most to the least as PAM>Control>BC+PAM>BC for Marl soil and with a slight change as PAM>Control>BC>BC+PAM for Loess soil (Table 2 and Fig. 4). The mean infiltration rates of the BC treated plots decreased by 0.23 and 0.05%, respectively, for Marl and Loess soils (Fig. 4). The results also showed that PAM application could increase the soil infiltration rate only 0.02 and 0.13% respectively for Marl and Loess soils. In BC+PAM treatment, mean infiltration decreased by 0.17% for both Marl and Loess, compared to control (Fig. 4). We hypothesized that the decreasing of infiltration results from macropores reduction that occurred when BC and PAM applied. In this regards, the soil sorptivity and the BC particle size are important factors as reported by Sun et al. (2018) for a coastal saline soil (silty loam) amended with non-sieved and sieved BC. Furthermore, in the present study the amendments were only applied to the soil surface. So that, it was supposed that the amendments did not significantly improve the overall pore structure of the soil column (Sun et al., 2018). The different mechanisms of BCs were also emphasized by Bayabil et al. (2015). They concluded that wood (oak) and corn based BCs respectively decreased and slightly increased moisture retention of clayey acidic soils. The results verified similar trends for infiltration decreasing and increasing of Marl and Loess soils under study treatments. This finding could be attributed to the relatively similar values of bulk density of the study soils (1.12 g cm^{-3} for Marl and 1.13 g cm^{-3} for Loess). However, the rate of infiltration decreasing and increasing is varied. It is might be related to the soil bulk density affectability from study treatments (Hseu et al., 2014; Alkhasha et al., 2018) that is not measured in this work.

Our results are consistent with Gopal et al. (2019) findings who also reported the decrease in infiltration as the result of BC amendments. Verheijen et al. (2010) and Kinney et al. (2012) also confirmed that the water repellency increased after biochar application, thus resulting in a decrease in water infiltration. The strong relationship between soil water repellency and low infiltration rates and increased runoff was reported in other studies (e.g., Villagra-Mendoza and Horn, 2019). The feedstock and the pyrolysis conditions are two determinant factor to the water repellency intensity of BC as mentioned by Kinney et al. (2012). In the present research, we treated the soil through surface application of BC. Page-Dumroese et al. (2015) explained that the surface application of BC resulted in greater water repellency than BC mixed into the soil. Roozbeh et al. (2011) observed a reduction with infiltration rates due to PAM application for loam soils of south-western Iran. Adversely, the effect of PAM on increasing soil water holding capacity has been reported by Dorraj et al. (2010) for the sandy clay loam and loamy sand soils of Zanjan, Iran.

Fig. 4

3.2. Water quality components

3.2.1. pH

Fig. 5 shows pH of runoff laden sediments collected from plots treated by different amendments for two study soils with non-significant differences ($P>0.05$). PAM applications partially lowered the pH compared to the control plot. In addition, the pH values of runoff generated from BC and BC+PAM little increased compared to control. The fitted models between runoff amount and pH values showed a fairly strong coefficient of determination ($R^2> 0.55$) under all treatments particularly in Loess soil (Fig. 6). The increase in the soil pH of the Marl and Loess soils from BC application might have also amplified soil dispersal (e.g., Novak et al., 2009; Lee et al., 2015) leading to a decline in infiltration compared with the PAM treatment that had no increasing effect on the soil pH (Table 2 and Fig. 5).

The pH increase could be subject to the both primary of study soil pH and the raw materials used for BC production. For Marl and Loess soils, the initial soil pH, was respectively about 7.68 and 8.2. In addition, the pH difference between control and treated runoff by BC is very small and non-significant (P>0.11). Our findings showed similar trends established in various studies (e.g., Novak et al., 2009; Biederman et al., 2013; Lee et al., 2015) involving application of BC in increasing soil pH. The alkaline nature of BC, likely having a liming influence in the soils. For instance, Lu et al. (2012) reported that incorporation of sludge BC increased soil pH due to the alkalinity of the sludge. Blanco-Canqui (2019) through a review of relationship between BC and water quality concluded that the BC effect on water quality was depended on the BC feedstock, pyrolysis temperature, application amount, time after application, and its co-application with other amendments. Besides, pH of 11.02, 6.42, 6.60, 6.17 and 6.62 were reported for BC, loam soil-control, BC treated soil, PAM treated soil, and BC+PAM treated soil by Lee et al. (2015). They conducted the chemical analysis after an 11-month erosion experiment and the results showed that the BC and PAM application resulted in significant higher soil pH.

Fig. 5

Fig. 6

3.2.2. Electrical conductivity (EC)

The BC and BC+PAM applications significantly (P<0.05) increased the runoff EC of the two tested soils (Fig. 7). Since the main target of application of soil amendments is rehabilitation of degraded soils and preparation of the appropriate bed for vegetation growth, providing information about the EC variation due to application of amendment is essential. Butnan et al. (2015) mentioned that the BC application leads to releasing basic cations into the soil and consequently results in increasing EC.

PAM alone did not increase EC of the released runoff. At both Marl and Loess soils, there was no differences between control and PAM, and no differences between BC and BC+PAM treatments (Table 3). The runoff EC for control, BC, PAM and BC+PAM were respectively 492±25, 2410±652, 491±37, and 2386±255 µS cm^{-1} for Marl soil; and 466±23, 3244±418, 453±17 and 3082±400 µS cm^{-1} for Loess soil. The high value of coefficient of determination (R^2>0.87) were observed between runoff volume and EC for all treatments except PAM at Marl soil (Fig. 8). The obtained results for all treatments except PAM assessed the ability of the obtained models to predict or explain the EC in the regression setting. The increase in EC might be corresponded to the dissolution of BC in the water. In our study, PAM did not increased the EC that is in consisted with Tafti et al. (2016) finding. Sadeghi et al. (2020) proved the negative effects of BC on water quality parameters and reported an EC increasing in runoff after BC application.

Fig. 7

Fig. 8

Table 3

3.3. Erosion components

The main results of erosion components and their statistical analysis are presented in the Table 4, respectively.

Table 4

3.3.1. Soil loss and sediment yield

BC and PAM reduced soil loss of Marl respectively by 14.07 and 7.43%, whilst, BC+PAM increased the soil loss by 10.43% in comparison with the control. All the treatments were demonstrated to be successful in reducing soil loss generated from the Loess soil, so that, BC was the most effective additive in this regard ($P>0.05$; Table 4).

The application of BC (3.38-78.35%) and PAM (14.87-36.45%) reduced the sediment yield for both studied soils of this research ($P>0.05$). Besides, BC+PAM increased the sediment yield (5.07%) for Marl soil and reduced the sediment yield (8.31%) for Loess soil ($P>0.05$). Total sediment yield was lowest for PAM (5.80 g l^{-1}), and highest for BC+PAM (7.15 g l^{-1}) for Marl soil. The sediment yield induced from BC+PAM treatment was greater than control (6.81 g l^{-1}) indicating negative effects of BC+PAM treatment for Marl soil conservation. However, all treatments decreased the sediment yield for Loess soil compared with control, so that the lowest and the highest value were attributed to BC (2.07 g l^{-1}) and control (9.56 g l^{-1}), respectively (Table 4 and Fig. 9). The results verified different mechanisms of individual and combined applications of BC and PAM on the soil loss and sediment. It is hypothesized that the obtained minor positive effects of adding individual and combined BC and PAM in Loess soil and only individual BC and PAM in Marl soil provided by their effects on the particles flocculation and aggregate stabilization. While, the adverse effect of BC+PAM for Marl soil could be interpreted by synergy impact of hydrophobicity caused by BC and PAM, simultaneously as well as the constructional nature, high deposits of silt and low clay of Marl soil. Existence of calcium carbonate, gypsum, anhydrite and salt in this soil also could help to this negative effect. In addition, in the present study, only BC powder and anionic PAM were used. It is also supposed that using different types of these amendments (e.g., different particle sizes of BC, powder type of PAM or its cationic type) might have different impacts. Similar variations in mechanisms of BC and PAM were displayed by other researchers, too. For instance, Wang et al. (2011) indicated that the PAM application did not prevent the soil erosion. Mbagwu and Piccolo (1997) and Bayabil et al. (2015) have found that BC increased the soil macro-aggregate stability by 20-130%; depends on soil texture, clay mineralogy, as well as elemental constituents of amendments. Lee et al. (2015) attributed the decrease in soil loss to clay flocculation and aggregate stabilization made by PAM, and water adsorption capacity provided by BC. Their finding verified a maximum reduction of 19.9% in soil loss due to application of BC as compared to that of the control. Another potential explanation for the fact was that the BC cations and soil particles were bridged by trap water molecules under Coulombic and van der Waals forces thereby contributed to soil loss and sediment reduction. Blanco-Canqui et al. (2019) also reported that the BC application reduces soil loss by 11 to 78% indicating the high its variability. The reduction benefit of BC was differently reported by Sadeghi et al. (2020) under field experimental circumstances.

Fig. 9

3.3.2. Splash erosion

BC and PAM in comparison with control reduced the different type of splash erosion including up, down and net splash erosions of Marl and Loess soils (Fig. 10). Our findings showed that PAM, BC and BC+PAM respectively were the best for up, down and net splash erosions control for the Marl soil, even if other treatments were also efficient. The non-significant ($P>0.05$) effect of study treatments ranged from -26.18 (PAM; Net splash erosion) to 91.03% (BC+PAM; Net splash erosion). In addition, for Loess soil, the effective treatments were set as BC, BC, and PAM for up, down and net splash erosions control, respectively. The non-significant ($P>0.05$) effect of the studied treatments on Loess soil ranged from 13.69 to 72.50% associated with BC+PAM and PAM respectively for up and net splash erosion control (Fig. 10). Totally, splash erosion variability from BC and PAM is not a well-known, though its relevance and importance is often highlighted in the literature.

The reduction in the disintegration of soil particles from the bulk was measured by Hseu et al. (2014) for the mudstone formation of Taiwan. Moreover, the porosity (4-27%) and soil aggregate size (0.59-0.94 mm), as major determinant factors for the soil structure, increased after 168 days of BC application (Hseu et al., 2014). According to Bayabil et al. (2015) reports, BC bonds with soil surfaces mineral through carboxylic and phenolic functional groups, hence, improves the soil structural aggregation and stability. The atomic ratios of hydrogen:carbon (H:C) and oxygen:carbon (O:C) of used BC are another variables could affect the BC efficiency on the soil erosion control. Because they are indicative of the bonding arrangement and polarity (Sun et al., 2017). They are also correlated with the degree of thermochemical alteration during BC pyrolysis. Although in the present study, they are not calculated and it is suggested to measure for future soil erosion and water conservation studies. Sun et al. (2017) measured the H:C and O:C ratios for 60 BC types and their primary raw materials. They concluded that the raw materials and BCs (produced at 500 °C) respectively have the ranges of 0.94 to 2.43 and 0.42 to 0.81 for H:C ratio and 0.05 to 1.00 and 0 to 0.27 for O:C ratio.

Lee et al. (2015) also denoted that soil particle detachment could be eliminated using BC application due to absorption of raindrop energy or buffering on soil surface. Recently, Yakupoglu et al. (2019) showed that PAM reduced soil transported by splash considerably due to its charge density and molecular weight. Briefly, we showed that during the rainfall simulation, the resistance of treated soils with BC and PAM against erosion by raindrop splash increased in comparison with control soils. It was observed that the dissolved molecules of PAM were partially absorbed on the soil particles and partly enhanced the aggregate stability leading to decreasing in splash rates during the rainfall event. The results were in agreement with the previous studies (e.g. Sadeghi et al., 2016c; Sadeghi et al., 2020) which confirmed the conservation effects of PAM on reducing net, upward and downward-splash erosion of the silty loam soil.

Fig. 10

4. Conclusion

Application of biochar (BC) and polyacrylamide (PAM) to soil have been suggested as a non-structural best management practices (BMPs) to mitigate runoff potential and soil erosion. Towards this, the present paper applied these two soil amendments for conservation of Marl and Loess soils of northern Iran under rainfall simulation in laboratory conditions. The effect of individual and combined application of BC and PAM have been assessed undesirable and highly variable for different hydrologic components for the study soils. However, application of BC and PAM in individual and combined form could successfully suppress splash erosion as the most important and initial stage of water erosion. It can be concluded from the results that PAM could not successfully improve the performance of BC in soil and water conservation of Marl and Loess soils. This study brings attentions to decision makers because we have determined almost the worse situations of runoff, water quality and erosion components under BC application even in combination with PAM for both Marl and Loess soils. It clearly proved different performances of study amendments for runoff and soil loss control in soils, which are intrinsically sensitive to water and soil losses. Nonetheless, more insightful investigations with other amendments, different manners of application (e.g., allowance time after application, type and time of usage), different plot scales and BCs with different particle sizes, shape, and porosity are recommended as complementary research to be considered in the future studies to find the most effective and applicable technology for the optimal use of the soil resources.

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Figures Captions

Fig. 1. Flow chart for the detailed methodology for testing applicability of BC and PAM for soil and water conservation for two-soil erosion sensitive of Marl and Loess under laboratory simulation

Fig. 2. General views of the areas of soil origins of Marl (a) and Loess (b), samples of Marl (c) and Loess (d) soils and specimens of BC (e) and PAM (f)

Fig. 3. Overview of the experimental set up with the rainfall simulator (up) and splash cups setting (down)

Fig. 4. Changes (%) in runoff components after application of different treatments for the two study soils

Fig. 5. Results of treatments effect on runoff-pH for the two study soils

Fig. 6. Relationships between runoff-pH and runoff volume for the two study soils

Fig. 7. Results of treatments effect on runoff-EC for the two study soils

Fig. 8. Relationships between runoff-EC and runoff-values for the two study soils

Fig. 9. Changes in soil loss and sediment concentration after treatments application for the two study soils

Fig. 10. Changes in components of splash erosion under different treatments for the study soils

Table 1 Characteristics of vinasse and biochar (Percent per weight)

Element	Vinasse	Biochar (BC)
Na_2O	1.852	1.870
MgO	1.563	2.787
Al_2O_3	2.017	3.377
SiO_2	9.602	15.502
P_2O_5	0.418	0.604
SO_3	7.087	8.592
K_2O	10.021	11.007
CaO	10.93	18.578
TiO_2	0.191	0.306
MnO	0.031	0.040
Fe_2O_3	1.579	2.469
Ni	0.010	0.010
Zn	0.064	0.092
Br	0.064	0.003
Rb	0.004	0.003
Sr	0.033	0.040
Zr	0.008	0.008
Loss on Ignition	49.760	29.780

Table 2 Results of hydrological components of control and treated plots for the two studied soils

Runoff component	Soil Type	Treatment	Mean	Standard Deviation
Time to runoff (s)	Marl	Control	196.67	82.19
		BC	225.00	15.90
		PAM	153.33	47.32
		BC+PAM	124.67	20.74
	Loess	Control	103.33	30.64
		BC	116.67	26.25
		PAM	141.67	29.53
		BC+PAM	116.67	33.99
Runoff coefficient (%)	Marl	Control	38.66	22.44
		BC	49.94	6.91
		PAM	37.70	5.20
		BC+PAM	47.29	7.41
	Loess	Control	46.42	12.35
		BC	48.79	16.20
		PAM	40.07	9.58
		BC+PAM	54.70	12.10
Infiltration (ml)	Marl	Control	413.45	1.87
		BC	412.51	0.43
		PAM	413.52	0.58
		BC+PAM	412.73	0.62
	Loess	Control	412.80	1.03
		BC	412.60	1.35
		PAM	413.33	0.80
		BC+PAM	412.11	1.01

Table 3 Groups of EC results induced from different treatments for two study soils

Treatment	N	Marl		Loess	
		Subset for alpha = 0.05		Subset for alpha = 0.05	
		1	2	1	2
PAM	3	0.49		0.45	
Control	3	0.49		0.47	
BC+PAM	3		2.39		3.08
BC	3		2.41		3.24
Significant Level		1.00	0.95	0.97	0.59

Table 4 Results of erosion components of control and treated plots for the two study soils

Erosion components	Soil Types	Treatments	Mean	Standard Deviation
Total soil loss (g)	Marl	Control	19.43	14.76
		BC	16.70	8.84
		PAM	17.99	1.36
		BC+PAM	21.46	6.66
	Loess	Control	30.56	17.04
		BC	5.13	1.08
		PAM	19.97	12.34
		BC+PAM	28.96	12.66
Total sediment yield (g l^{-1})	Marl	Control	6.81	2.13
		BC	6.58	2.76
		PAM	5.80	0.48
		BC+PAM	7.15	1.31
	Loess	Control	9.56	4.41
		BC	2.07	0.22
		PAM	6.08	2.50
		BC+PAM	8.77	3.04
Upward-splash erosion (g)	Marl	Control	0.20	0.06
		BC	0.14	0.08
		PAM	0.09	0.07
		BC+PAM	0.13	0.03
	Loess	Control	0.06	0.03
		BC	0.03	0.03
		PAM	0.04	0.01
		BC+PAM	0.05	0.02
Downward-splash erosion (g)	Marl	Control	0.65	0.30
		BC	0.43	0.08
		PAM	0.26	0.25
		BC+PAM	0.17	0.12
	Loess	Control	0.10	0.03
		BC	0.05	0.05
		PAM	0.05	0.02
		BC+PAM	0.06	0.03
Net-splash erosion (g)	Marl	Control	0.45	0.24
		BC	0.29	0.08
		PAM	0.17	0.19
		BC+PAM	0.09	0.12
	Loess	Control	0.04	0.00
		BC	0.02	0.02
		PAM	0.01	0.01
		BC+PAM	0.02	0.02

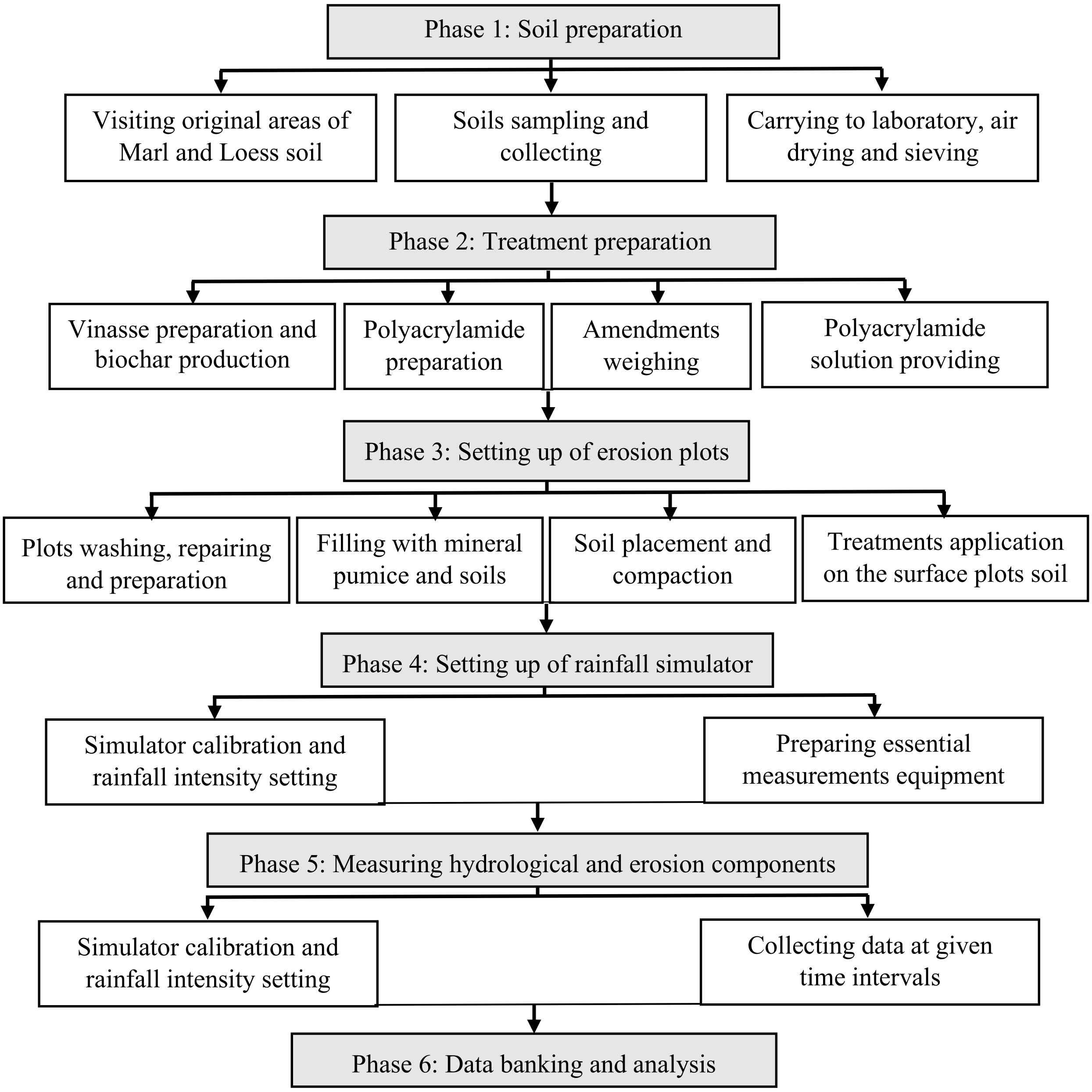

Phase 1: Soil preparation
Visiting original areas of Marl and Loess soil
Soils sampling and collecting
Carrying to laboratory, air drying and sieving
Phase 2: Treatment preparation
Vinasse preparation and biochar production
Polyacrylamide preparation
Amendments weighing
Polyacrylamide solution providing
Phase 3: Setting up of erosion plots
Plots washing, repairing and preparation
Filling with mineral pumice and soils
Soil placement and compaction
Treatments application on the surface plots soil
Phase 4: Setting up of rainfall simulator
Simulator calibration and rainfall intensity setting
Preparing essential measurements equipment
Phase 5: Measuring hydrological and erosion components
Simulator calibration and rainfall intensity setting
Collecting data at given time intervals
Phase 6: Data banking and analysis

Fig. 1

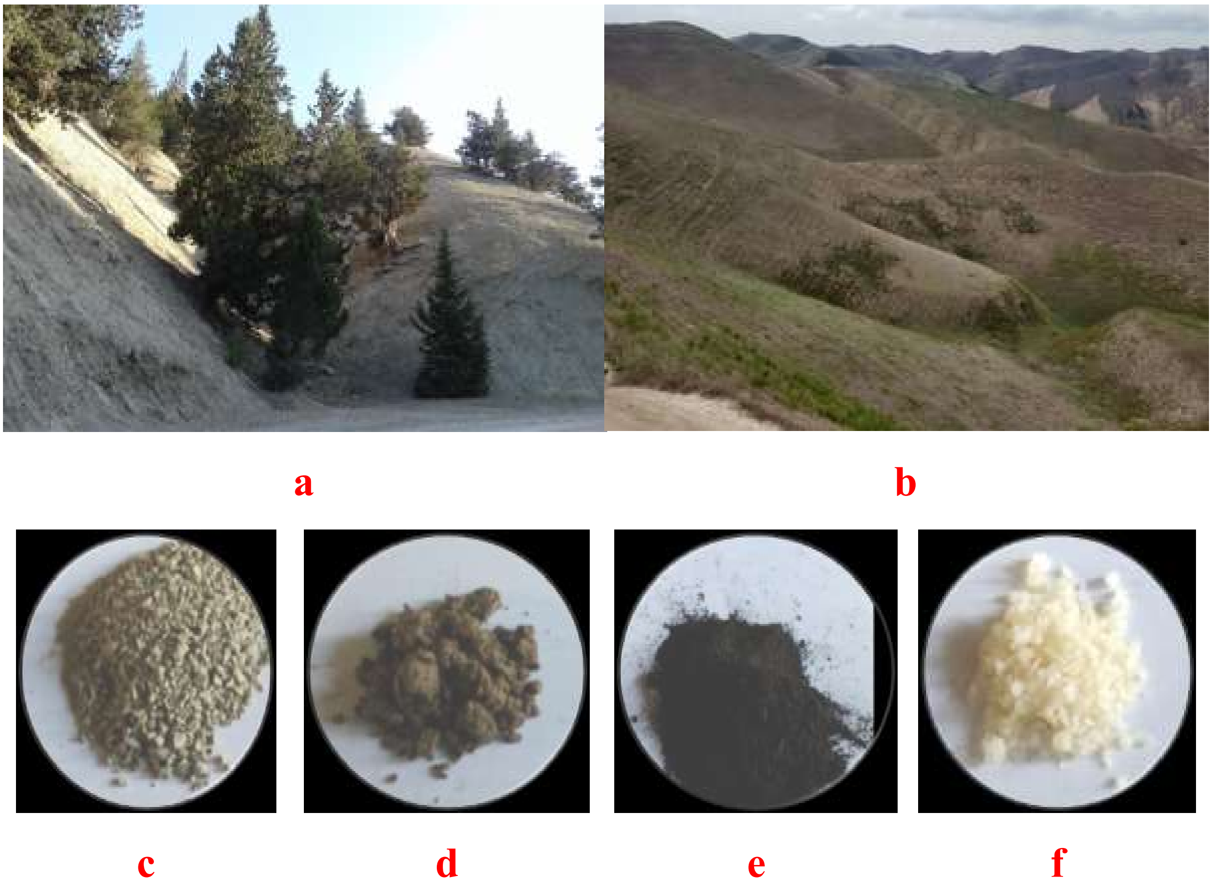


Fig. 2


Nozzles
Rainfall Simulator
Rainfall and Erosion Simulation Laboratory
Plots Lifting System
Experimental Plots
Pump
Water Tank
Water collectors
20%

Fig. 3

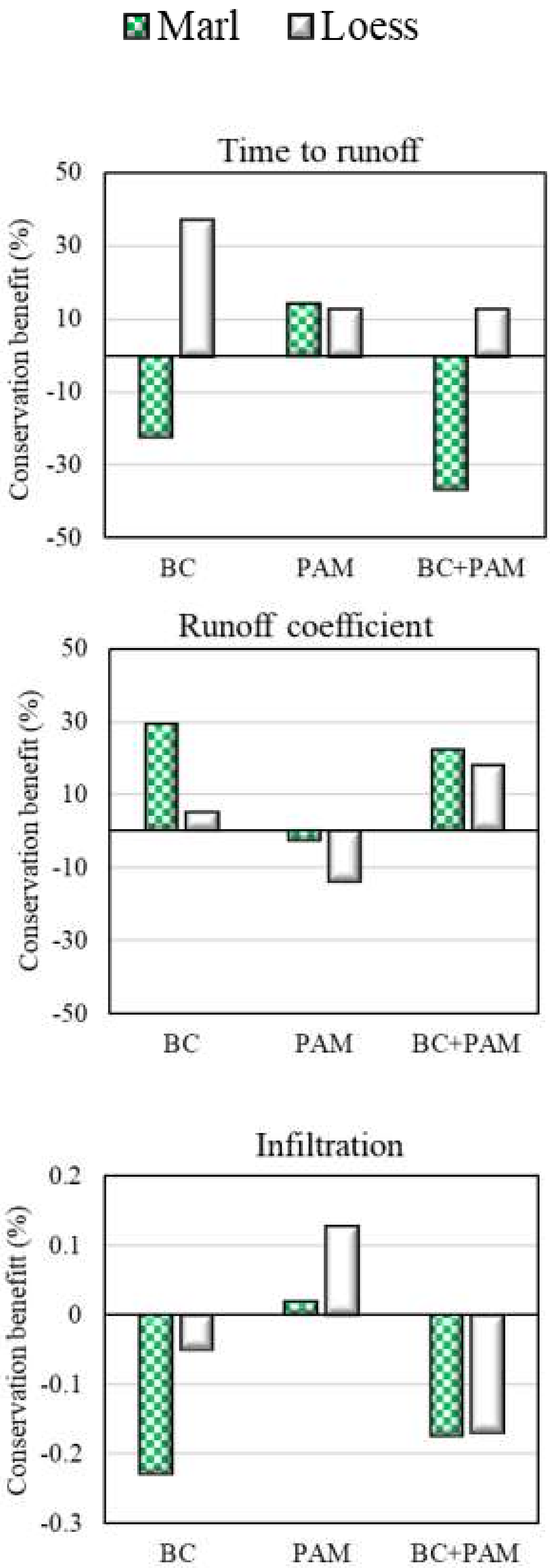

Marl
Loess
Time to runoff
Conservation benefit (%)
50
30
10
-10
-30
-50
BC
PAM
BC+PAM
Runoff coefficient
Conservation benefit (%)
50
30
10
-10
-30
-50
BC
PAM
BC+PAM
Infiltration
Conservation benefit (%)
0.2
0.1
0
-0.1
-0.2
-0.3
BC
PAM
BC+PAM

Fig. 4

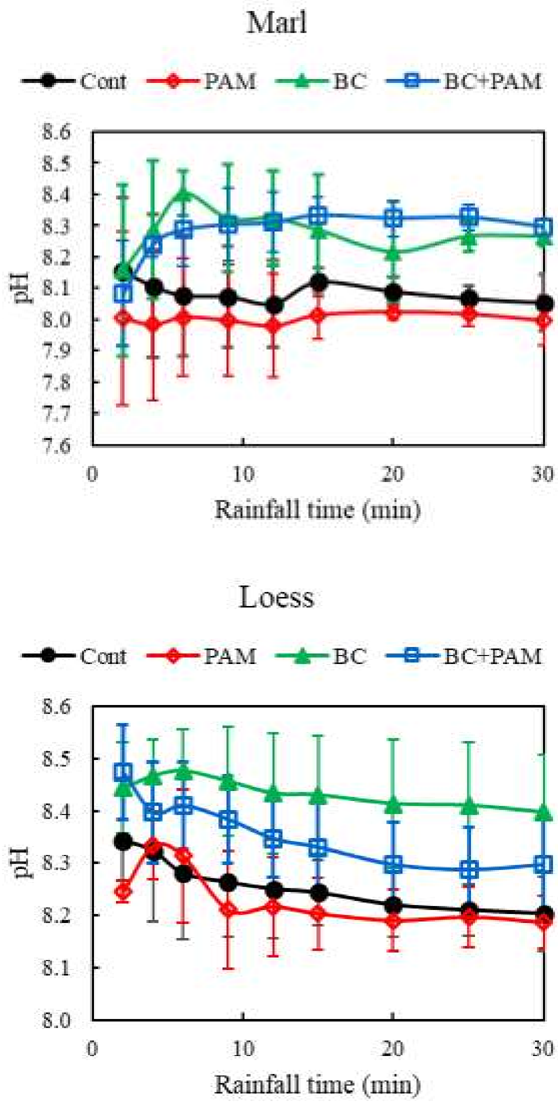

Marl
Cont
PAM
BC
BC+PAM
8.6
8.5
8.4
8.3
8.2
8.1
8.0
7.9
7.8
7.7
7.6
pH
0
10
20
30
Rainfall time (min)
Loess
Cont
PAM
BC
BC+PAM
8.6
8.5
8.4
8.3
8.2
8.1
8.0
pH
0
10
20
30
Rainfall time (min)

Fig. 5

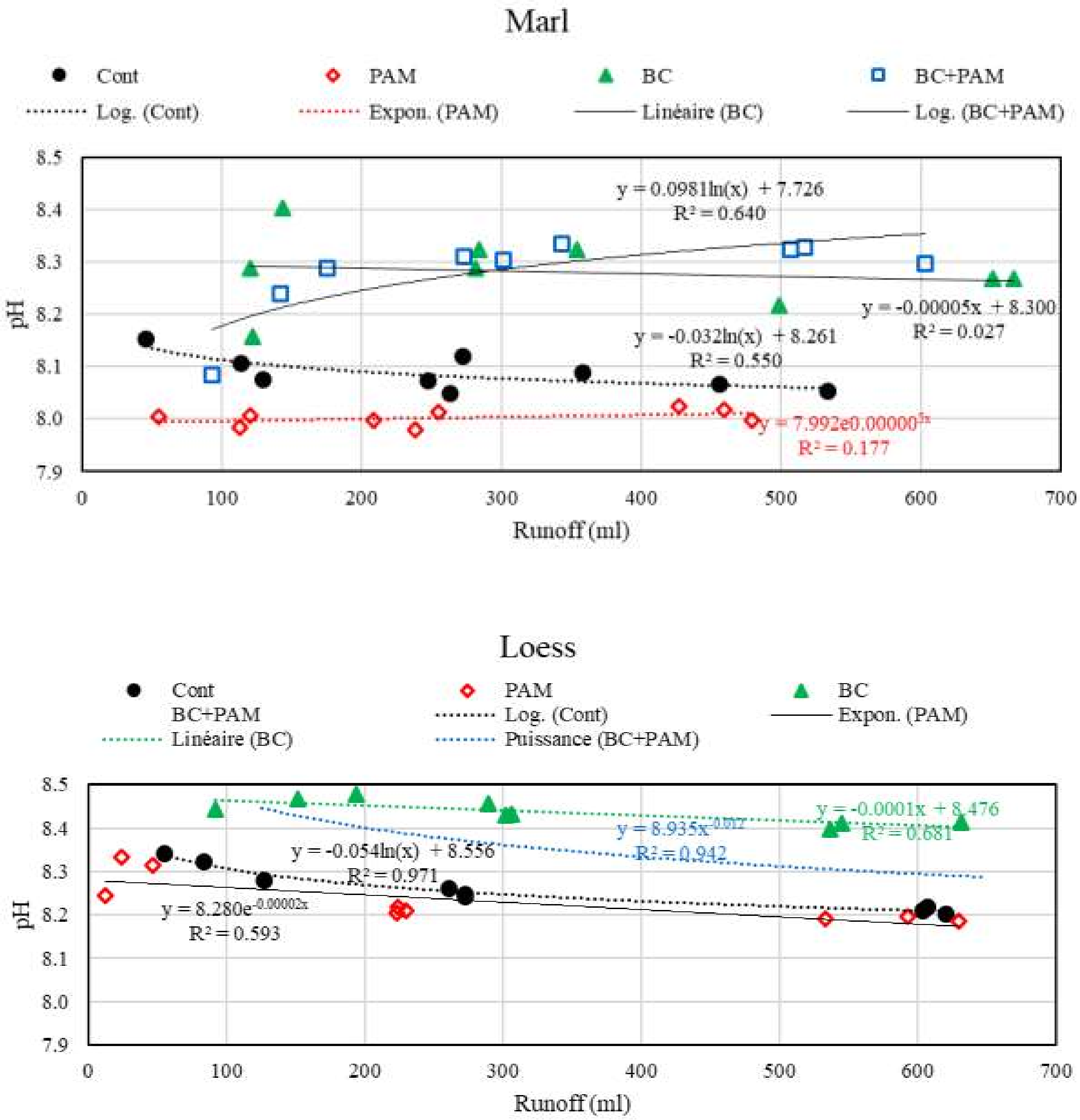

Marl
Cont
PAM
BC
BC+PAM
Log. (Cont)
Expon. (PAM)
Linéaire (BC)
Log. (BC+PAM)
y = 0.0981ln(x) + 7.726
R² = 0.640
y = -0.00005x + 8.300
R² = 0.027
y = -0.032ln(x) + 8.261
R² = 0.550
R² = 0.177
pH
Runoff (ml)
Loess
Cont
PAM
BC
BC+PAM
Log. (Cont)
Expon. (PAM)
Linéaire (BC)
Puissance (BC+PAM)
y = -0.0001x + 8.476
R² = 0.681
R² = 0.942
y = -0.054ln(x) + 8.556
R² = 0.971
y = 8.280e-0.00002x
R² = 0.593
pH
Runoff (ml)

Fig. 6

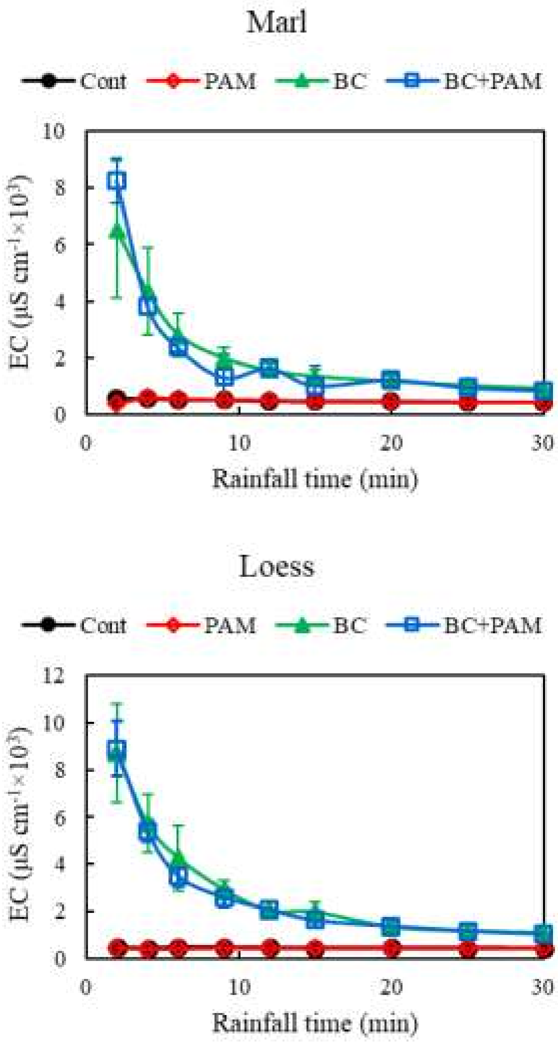
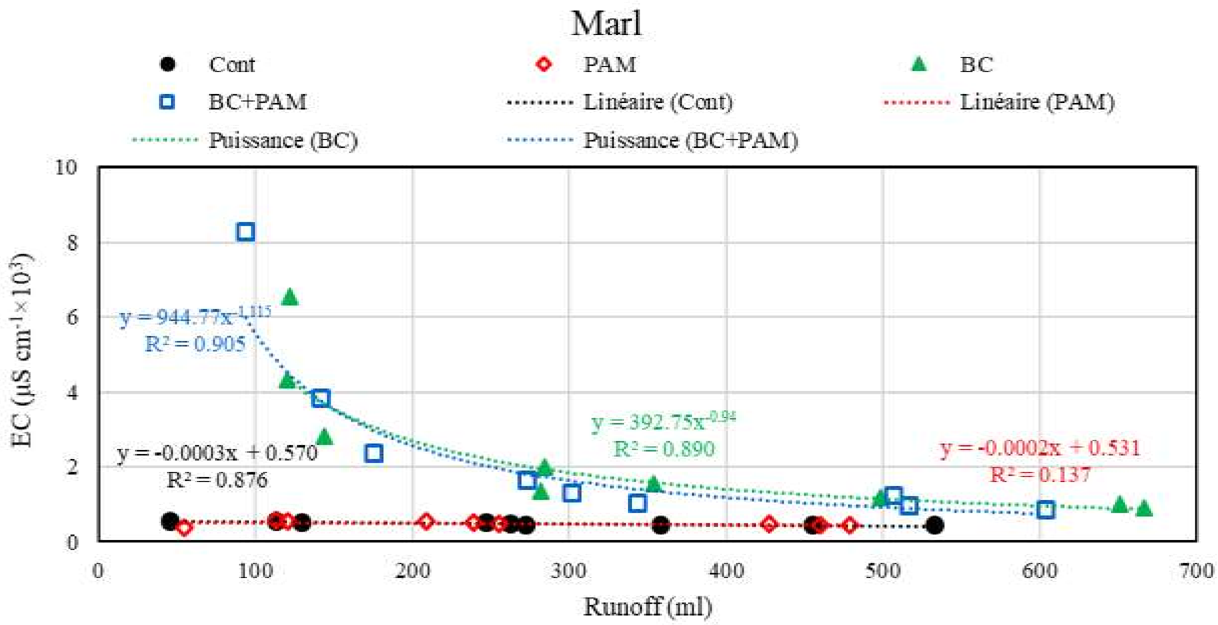

Marl
Cont
PAM
BC
BC+PAM
10
8
6
4
2
0
EC (µS cm-1×10³)
0
10
20
30
Rainfall time (min)
Loess
Cont
PAM
BC
BC+PAM
12
10
8
6
4
2
0
EC (µS cm-1×10³)
0
10
20
30
Rainfall time (min)

Fig. 7


Marl
Cont
PAM
BC
BC+PAM
Linéaire (Cont)
Linéaire (PAM)
Puissance (BC)
Puissance (BC+PAM)
EC (µS cm-1×10³)
Runoff (ml)
y = 944.77x-1.115
R² = 0.905
y = -0.0003x + 0.570
R² = 0.876
y = 392.75x-0.94
R² = 0.890
y = -0.0002x + 0.531
R² = 0.137

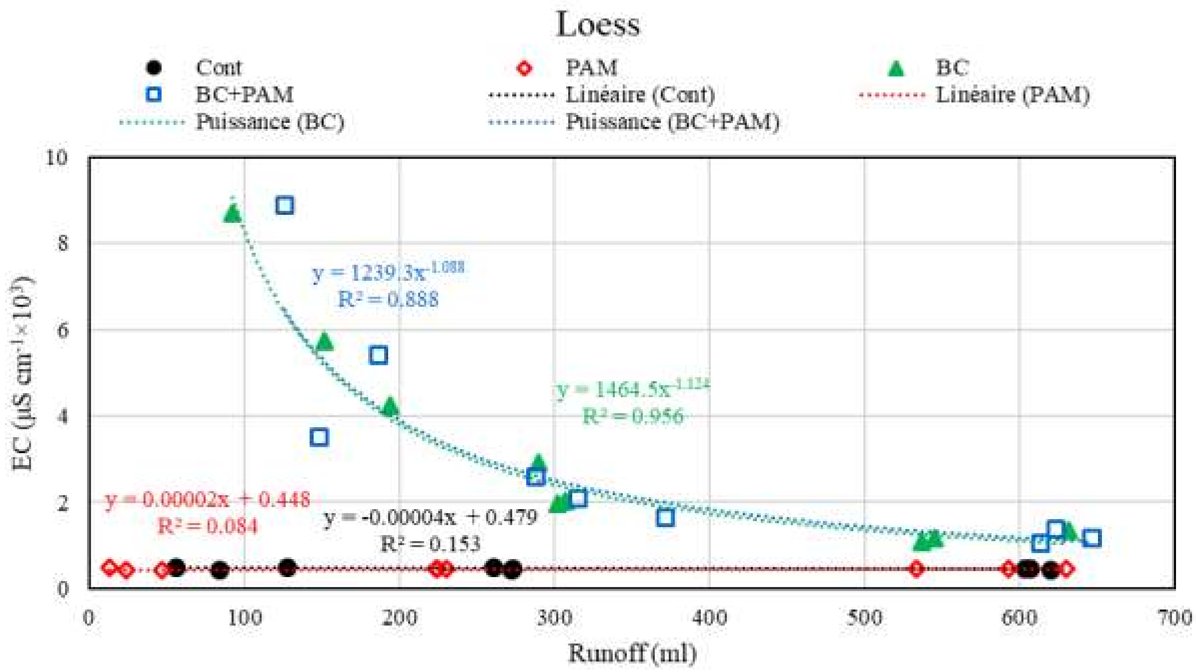

Loess
Cont
PAM
BC
BC+PAM
Linéaire (Cont)
Linéaire (PAM)
Puissance (BC)
Puissance (BC+PAM)
EC (µS cm-1×10³)
Runoff (ml)
y = 1239.3x-1.088
R² = 0.888
y = 1464.5x-1.124
R² = 0.956
y = 0.00002x + 0.448
R² = 0.084
y = -0.00004x + 0.479
R² = 0.153

Fig. 8

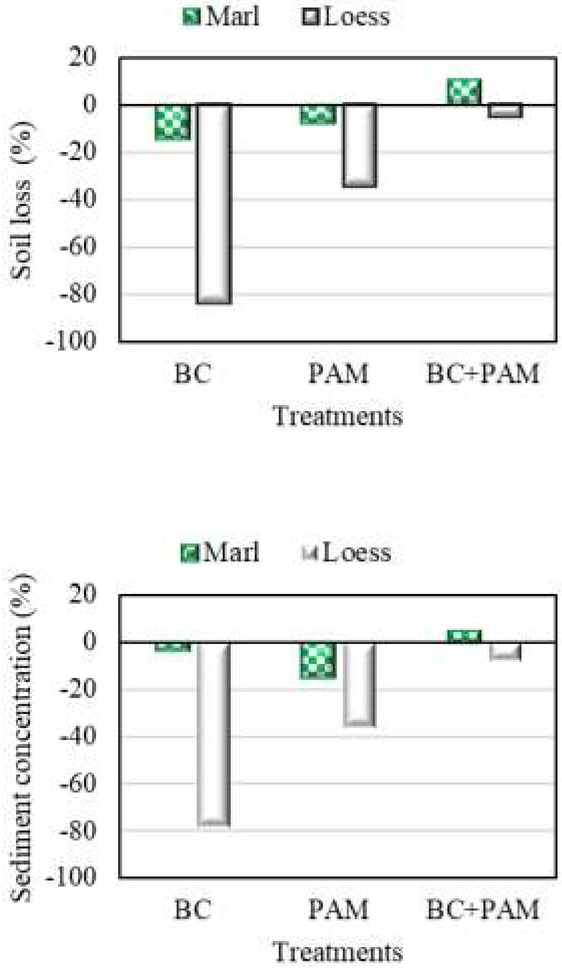
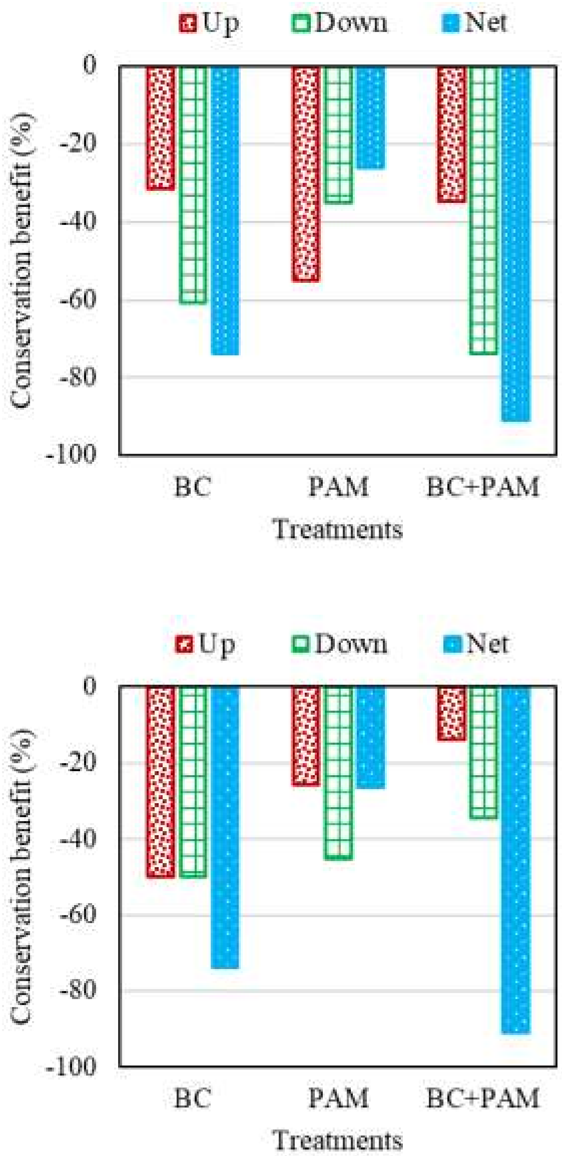

Marl
Loess
20
0
-20
-40
-60
-80
-100
Soil loss (%)
BC
PAM
BC+PAM
Treatments
Marl
Loess
20
0
-20
-40
-60
-80
-100
Sediment concentration (%)
BC
PAM
BC+PAM
Treatments

Fig. 9



Up
Down
Net
0
-20
-40
-60
-80
-100
Conservation benefit (%)
BC
PAM
BC+PAM
Treatments
Up
Down
Net
0
-20
-40
-60
-80
-100
Conservation benefit (%)
BC
PAM
BC+PAM
Treatments

Fig. 10