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## The hydrologic behavior of Loess and Marl soils in response to biochar and polyacrylamide mulching under laboratorial rainfall simulation conditions

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

3  
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21

## 22 Abstract

23 Due to the high costs of soil erosion control actions, the precise selection of practical  
24 techniques is requisite for a sustainable land management. **To proper application of anti-**  
25 **erosion measures, a good knowledge from the behavior of the soil erosional and hydrological**  
26 **properties is required.** Many researchers indicated that biochar (BC) and polyacrylamide  
27 (PAM) are **important** soil amendments to enhance soil physical and hydrological  
28 characteristics. However, little is known about the response and mechanisms of two prone-  
29 erosion soils of Marl and Loess against the individual and combination of the BC and PAM  
30 applications. Therefore, the present study was planned to test the effectiveness of these anti-  
31 erosive techniques on variability of 1) hydrological components (i.e., time to runoff, runoff  
32 coefficient and infiltration); 2) runoff quality components (i.e., pH and electrical  
33 conductivity, EC) and 3) erosion components (i.e., upward-splash, downward-splash and net-  
34 splash erosion, soil loss and **sediment concentration**) at two soils of Marl and Loess under  
35 rainfall simulation conditions. The study treatments were consisted of control (200 ml water),  
36 BC (800 g m<sup>-2</sup>), PAM (2 g m<sup>-2</sup>), and BC (800 g m<sup>-2</sup>) + PAM (2 g m<sup>-2</sup>). The treatments were  
37 sprayed uniformly over the small plots (0.3 × 0.5 × 0.5 m in dimensions; 0.25 m<sup>2</sup> in area)  
38 with slope of 20% in three replicates. The rainfall with an intensity of 50 mm h<sup>-1</sup> and  
39 duration of 0.5 h was applied. The results showed that **a)** only PAM delayed the time to  
40 runoff with rate of 41.4% compared to control treatment at Marl soil and **all treatments**  
41 **delayed the time to runoff of Loess soil (BC=37.1% and PAM=BC+PAM=12.9%); b)** among  
42 the study treatments, PAM **had the greatest effect** due to decreasing runoff coefficient by 2.47  
43 and 13.67%, and improving infiltration by 0.02 and 0.13% at Marl and Loess soils,  
44 respectively; **c)** BC and BC+PAM increased the pH values of runoff whilst the PAM  
45 applications partially reduced the pH compared to the control plot at both study soils; **d)** the  
46 BC and BC+PAM applications significantly (P<0.05) increased EC of runoff released from

47 both tested soils. In contrary, PAM had the least influence on EC of the runoff in comparison  
48 with the control condition; **e)** the maximum effect on soil loss reduction was attributed to BC  
49 for Marl and Loess soils respectively with rates of -14.07 and -83.21%. In addition, the  
50 maximum benefit on sediment concentration reduction was attributed to PAM (-14.87%) and  
51 BC (-78.35%) respectively at Marl and Loess soils; **f)** all treatments reduced the upward-  
52 splash, downward-splash and net-splash erosion at both study soils in range of -13.69%  
53 (BC+PAM at Loess soil) to -73.68% (BC at Marl soil) in comparison with control.

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

56

## 57 **1. Introduction**

58 Soil erosion is an important process of terrestrial degradation in many parts of the world  
59 (Pereyra et al., 2020; Zaimes et al., 2020). **It also lead** to exacerbate poverty and food insecurity  
60 in the densely populated areas. Since, it affects not only the soil resources but also has  
61 influence on the water, vegetation, landscape, and microclimatic components of ecosystems  
62 (Hazbavi et al., 2019; Scholten and Seitz, 2019; Wüpper et al., 2019). New management and  
63 techniques are recently introduced to reduce soil erosion and to achieve goals related to land  
64 sustainability. Natural or synthetic soil amendments as non-structural best management  
65 practices (BMPs) are used to sustain appropriate soil and water resources properties (e.g.,  
66 Ekebafé et al., 2015; Liu et al., 2018; Ul Zaman et al., 2018). Application of proper soil  
67 amendments **for soil erosion control and water conservation** has become an increasingly  
68 common option to improve the land sustainability (e.g., Sadeghi et al., 2014; Behzadfar et al.,  
69 2017; Alkhasha et al., 2018). **The literature highlighted that** the addition of pyrogenic organic  
70 matter (biochar; BC) and polymers resulted in a plethora of predominantly reduction in the soil  
71 erosion and its components including runoff, soil loss and sediment yield (e.g., Hazbavi et al.,

72 2012; Soo et al., 2015; Sadeghi et al., 2016a, b and c; Kianian et al., 2018; Yakupoglu et al.,  
73 2019; Ao et al., 2019; Wang et al., 2019; Li et al., 2019; Villagra-Mendoza and Horn, 2019;  
74 Sanford and Larson, 2020). The use of BC produced from biomass waste is introduced as a  
75 sustainable solution for waste disposal in viewpoints of environmental, ecological and  
76 economical aspects (Ghezzehei et al., 2014). Besides, polyacrylamide (PAM) is produced into a  
77 long-chain synthetic polymer and is as a strengthening agent to soils in place against soil  
78 erosion (Soltani-Jigheh et al., 2019).

79 BC and PAM addition to soils could change the soil hydrology process through changes in the  
80 water holding capacity, water infiltration, runoff generation, soil drainage, soil water  
81 repellency, soil penetration resistance, and water delivery to plants (e.g., Dorraj et al., 2010;  
82 Wang et al., 2011; Kinney et al., 2012; Wei et al., 2014; Zong et al., 2016; Sadeghi et al.,  
83 2016a, b and c; Sandhu and Kumar, 2017). The effects of PAM and BC treatments in changing  
84 soil erosional and hydrological behaviors were mostly related to increasing clay flocculation,  
85 soil aggregation process and aggregate sizes (Hseu et al., 2014; Bayabil et al., 2015; Lee et al.,  
86 2015; Yakupoglu et al., 2019). Because different factors affecting the BC and PAM efficiency  
87 in the improving soil erosional and hydrological properties, various results were found in  
88 different regions of the world. A variety of characteristic in terms of climatic, especially in  
89 terms of rainfall variables (e.g., intensity, duration, frequency), edaphic (e.g., soil texture, soil  
90 structure, particle size distribution) and soil hydraulic (e.g., bulk density, saturated hydraulic  
91 conductivity) could be specified as determinant factors. Besides, the initial characteristics of  
92 BC and PAM treatments have been considered as potential source of change in their  
93 effectiveness on improving erosion and hydrological properties in terms of quantity and quality.  
94 For example, the type of raw material used to BC production is very critical. Sun et al. (2017)  
95 characterized 60 types of Chinese biomass waste and highlighted the resultant BC in terms of  
96 their candidacy for soil application. Their results verified the different effect of biomass

97 pyrolysis on the BC efficiency. The physical and chemical properties of BC and PAM and the  
98 method of their application need to be further considered as well. In this regard, Li et al. (2019)  
99 demonstrated that the different BC particle size and time of incubation changes the time to  
100 runoff initiation, runoff volume and erosion rate.

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

108 Previous studies suggest that both individual and combined application of BC and PAM have  
109 both short and long terms effects on soil erosion mitigation and hydrology process after  
110 application, ranging from a few days to several months or years. For example, Hseu et al.  
111 (2014) studied the impacts of BC made from rice hull biochar at rates of 2.5, 5, and 10%  
112 (w/w) on soil physical and erosion properties of a Mudstone slope land under incubation  
113 experiment (disturbed soil). Their findings only proved the positive effect of 10% BC on the  
114 water conductivity that leading a substantial macropores increasing and soil strength  
115 decreasing. The simulation results also showed the significant reduction (i.e., 35 to 90%) of  
116 soil loss after BC application. Sandhu and Kumar (2017) evaluated the impact of three plant-  
117 based BC materials (ponderosa pine, corn stover, switchgrass and wood residue); dairy  
118 manure; and manure+pinewood BC on the hydrological properties (i.e., soil water infiltration  
119 rate, soil water retention, and pore size distribution) of undisturbed soils. According to the  
120 experiment findings, the significant effect of BC and manure applications on soil  
121 hydrological behaviors especially a negative effect on soil penetration resistance was

122 obtained. Lee et al. (2018) investigated the effectability of erosion components from  
123 applications of wood BC+green waste dreg compost, and PAM for an undisturbed tropical  
124 soil. The higher effectiveness of BC than PAM was reported for runoff control and  
125 infiltration improvements. In the same vein, Ao et al. (2019) explored the high positive  
126 impact of PAM application, at an optimal rate of  $2 \text{ g m}^{-2}$ , on reducing runoff and soil  
127 splashing for the Kastanozem soil using indoor rainfall simulation. They reported that the  
128 PAM amendment highly controlled runoff and sediment amounts as well as ammonia and  
129 nitrate loss. Li et al. (2019) also investigated the effects of BC with various particle sizes on  
130 water erosion processes of cultivated Loess soil under laboratory experiments. They  
131 concluded that the total runoff volume and total erosion after BC additions with different  
132 particle sizes decreased up to some 31% with slight difference under no- and eight months-  
133 incubations. They reported the effectiveness of BC for soil conservation due to increasing of  
134 water-stable soil aggregates and saturated hydraulic conductivity ( $k_{\text{sat}}$ ). Further, Peng et al.  
135 (2019) evaluated the impacts of BC on interrill erosion developments for an undisturbed silt  
136 loam soil. They showed that BC improved the soil aggregate stability and ultimately reduced  
137 the interrill erosion potential at a maximum rate of 21.34%. Whilst, the BC could not affect  
138 runoff generation in comparison with that of control soil. Villagra-Mendoza and Horn (2019)  
139 determined the impact of wetting and drying conditions on the infiltration behavior of two  
140 BC amendments and to validate the performance of infiltration models. They found that the  
141 BC addition decreased infiltration due to the formation of narrower pores led to reduced  
142 infiltration capacity. The higher the BC dosage, the more resilient the treatment became  
143 concerning the changes on the water infiltration. Wang et al. (2019) studied the synergic  
144 influences of BC and PAM for coastal soil restoration in China. The soil cohesion was  
145 decreased due to BC application and considerably increased in result of PAM treatment. It  
146 was concluded that application of BC and PAM together improved the quality and stability of

147 study undisturbed silt loam soil. Yakupoglu et al. (2019) also applied PAM to measure its  
148 effect on the time to runoff, total runoff, sediment yield, and splash sediment yield at  
149 laboratory erosion plots. The results showed that PAM did not delay runoff initiation;  
150 however, it reduced the total runoff, sediment yield, and soil transported by the splash. In  
151 addition, Zhang et al. (2019) examined the effects of BC additions pyrolyzed from hickory  
152 hardwoods and seasoned oak to control runoff, and interrill erodibility of Loess-derived  
153 Miami soil, China. The BC treatment decreased the total runoff by 2.4–10.8% ( $p>0.05$ ) and  
154 increased the interrill erodibility by 20.4–29.2% ( $p<0.05$ ) under disturbed conditions. The  
155 high risk of BC for erosion intensification of sloping croplands was emphasized. Recently,  
156 the applicability of individual and combined application of vinasse-BC and PAM was  
157 evaluated by Sadeghi et al. (2020) under semi-real conditions (rainfall simulation on  
158 undisturbed soil in the field). Accordingly, the effective reduction in soil loss in Marl and  
159 Loess soils by PAM was reported. They also verified that BC differently affected runoff and  
160 soil loss control in Marl and Loess soils.

161 As it could be understood from the literature reviewed, in overall, the different results for  
162 various environmental conditions for both disturbed and undisturbed soils were observed.  
163 Both positive and negative effects of BC and PAM were attributed to various components of  
164 soil hydrology and erosion processes. In addition, how individual and combined BC and  
165 PAM application affect the hydro-erosional process have not been cleared for erosion-prone  
166 soils of Marl and Loess. Therefore, it is important to test the potential BC and PAM  
167 application in the laboratory to understand the different performances of study amendments  
168 for runoff and soil loss control in soils, which are intrinsically sensitive to water and soil  
169 losses. On the other hand, the executive managers of Iran are not sure to use the preventative  
170 approaches or remedial techniques for soil and water resources management in areas  
171 underlain by sensitive formations. Towards this, there is a particular need to collect more data



172 on the hydrological impacts of various amendments under laboratory experiments before  
173 their field application. It, obviously, facilitates appropriate investment on proper amendments  
174 leading to economically efficient and environmentally sound improvement of the land  
175 resources.

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

197 Although many research on the soil erosion assessment and hydrological process  
198 investigation have been conducted for Marl and Loess soils (Zobiri et al., 2018), knowledge  
199 on their controllability is still incomplete and there are considerable uncertainties, particularly  
200 with regard to the effectiveness of anti-erosion techniques in the Marl and Loess areas.  
201 Therefore, any conservation activity in order to control the soil erosion in Marl and Loess  
202 soils is of particular importance and has an acceptable economic justification (Sharifi, 2018;  
203 Sharifi and Shamirzadi, 2018). In the previous studies (Hazbavi et al., 2016; Sadeghi et al.,  
204 2016a; Sadeghi et al. 2020), the significant effect of application of Vinasse-BC at rate of 8 t  
205 ha<sup>-1</sup> for the runoff and erosion control for a sandy clay loam soil of northern Iran was proved.  
206 However, it was found that BC was being easily floated by the runoff water during rainfall  
207 events, which necessitates the amendment of an additive to improve the adherence. Sadeghi  
208 et al. (2020) recently applied BC and PAM individually and in combination to the small plot  
209 scales installed in field. Nonetheless, the field condition would not be expected fully  
210 controlled and therefore more control conditions were essentially needed to assess the  
211 comparative performance of the study amendments. According to the successful application  
212 of PAM in reducing runoff and soil erosion and its polymeric nature (i.e., linearly-linked,  
213 water-soluble acrylamide sodium acrylate copolymer, adhesive, easy to penetration), the  
214 present study was ultimately formulated with the aim to test the interactive effects of BC and  
215 PAM under laboratory simulation for two erosion-prone soils of Marl and Loess. The present  
216 study was conducted with the hypothesis that the application of combined BC and PAM to  
217 soil could improve the hydro-erosional variables of Marl and Loess soils more than their  
218 individual application as a result of the synergy effects caused by the presence of the higher  
219 number of pores and the higher surface area of BC compared with other amendments and  
220 adhesiveness nature of PAM. Towards this, the present study was planned to test the  
221 effectiveness of individual and combined application of BC and PAM on variability of 1)

222 hydrological components (i.e., time to runoff, runoff coefficient and infiltration); 2) runoff  
223 quality components (i.e., pH and electrical conductivity, EC) and 3) and erosion components  
224 (i.e., upward-splash, downward-splash and net-splash erosion, soil loss and temporal  
225 variation of sediment yield) at two soils of Marl and Loess under rainfall simulation  
226 conditions.

227

## 228 **2. Materials and Methodology**

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

232

### **Fig. 1**

233

#### 234 **2.1. Soils sampling and analyses**

235 Surface samples (0–20 cm depth) of both study soils that usually spread in northern Iran, and  
236 made from various parent materials, were nominated. The soil parent materials of study areas  
237 were Marl and Loess, respectively collected from Marzanabad (51° 23.3620' E and 36°  
238 28.6520' N; 568 m amsl; Mazandaran Province) and Maravetapeh (55° 26.1550' E and 37°  
239 35.9510' N; 409.6 m amsl; Golestan Province), Iran (Fig. 2). **The climates of Marzandabad  
240 and Maravehtapeh regions are semi-arid cold and semi-arid, respectively. The mean annual  
241 precipitation and temperature were respectively estimated about 432 mm and 12.0 °C for  
242 Marzanabad region, and in that respect were about 350 mm and 17.7 °C for Maravehtapeh  
243 region (Eteraf and Telvari, 2003; Amini Jahromi et al., 2008; Eteraf et al., 2014; Kheirfam et  
244 al., 2017).**

245 **The texture, pH, electrical conductivity (EC) and bulk density were respectively assessed  
246 silty clay loam, 7.68, 210  $\mu\text{S cm}^{-1}$  and 1.12  $\text{g cm}^{-3}$  for Marl soil; and in that respect were**

247 obtained loam silty, 8.20, 750  $\mu\text{S cm}^{-1}$  and 1.13  $\text{g cm}^{-3}$  for Loess soil (derivation  
248 methodology was similar to Eteraf and Telvari, 2003; Amini Jahromi et al., 2008; Eteraf et  
249 al., 2014; Kheirfam et al., 2017). The particle size distribution analysis demonstrated the 42%  
250 clay, 43% silt and 15% sand for Marl soil and 57% clay, 36% silt and 7% sand for Loess soil.

251

## 252 2.2. Study Treatments

253 Experimental treatments consisted of soil without amendments (i.e., control; 120 ml  $\text{m}^{-2}$  of  
254 tap water), BC powder (800  $\text{g m}^{-2}$ ), solute PAM (16.67  $\text{g l}^{-1} \text{m}^{-2}$  dissolved in 120 ml of tap  
255 water), and combined application of BC+PAM (firstly 800  $\text{g m}^{-2}$  of BC powder and over  
256 uniformly sprayed by 16.67  $\text{g l}^{-1} \text{m}^{-2}$  of PAM). The soil amendment and used tap water values  
257 were selected according to previous experiences and preliminary experiments to soil erosion  
258 and runoff mitigation (Hazbavi et al., 2012, 2016; Sadeghi et al., 2016a, b and c). BC was  
259 produced through pyrolysis of solid vinasse provided from Sugarcane Development  
260 Company of Khuzestan Province, Iran, for 6 h in temperature of 450°C (Sadeghi et al.,  
261 2016a). The essential characteristics of the vinasse and vinasse-BC are indicated in Table 1.

262

**Table 1**

263

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

267

**Fig. 2**

268

## 269 2.3. Experimental plots

270 In July 2019, experimental plots were set up in a completely randomized design to remove the  
271 effect of potential variable environmental conditions such as un-uniformity of rainfall intensity

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

289

#### 290 **2.4. Rainfall simulation**

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

297 7 m s<sup>-1</sup> and 1.18 mm, respectively, similar to the specifications reported for rains occurred in  
298 northern Iran (Sadeghi et al., 2013). The calibration of rainfall simulation were entirely  
299 conducted under laboratory conditions at the Soil Erosion and Rainfall Simulation Laboratory  
300 of Tarbiat Modares University, Faculty of Natural Resources, Noor, Mazandaran Province,  
301 Iran. The mean intensity of the simulated rains was also checked during each experiment to  
302 ensure the similarities among study events. An overview of rainfall simulation apparatus is  
303 shown in Fig. 3.

304

## 305 **2.5. Measurement of runoff and soil erosion components**

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

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

316 **The difference between rainfall and runoff was also considered as infiltration, since there was**  
317 **no seepage from the plots** (Hazbavi and Sadeghi, 2016; Sadeghi et al., 2016 a and b). The  
318 splash erosion induced by raindrop impacts was also measured using one splash cup with  
319 outside diameter of 25 cm, height of 10 cm, and an inside diameter of 10 cm and an inner  
320 edge height of 2.5 cm, placed at the center of each experimental plot (Sadeghi et al., 2016c)

321 and 2018) as demonstrated in Fig. 3. The eroded soils during whole rainfall event collected at  
322 upper (i.e., upward-splash) and lower (downward-splash) parts of the splash cups, then oven  
323 dried for 24 h at 105 °C and weighted. Finally, the subtracting splashed soils on upward and  
324 downward directions was considered as the net splash erosion (Sadeghi et al., 2016c and  
325 2018). Additionally, the pH and electrical conductivity (EC) of runoff samples were  
326 determined using portable pH and EC meters.

### 327 Fig. 3

328

## 329 2.6. Data analyses

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

339

## 340 3. Results and discussion

### 341 3.1. Runoff components

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

344

### Table 2

345

### 346 3.1.1. Time to runoff

347 Under the study conditions, time to runoff ranged from 103.33 s to 225 s depending upon the  
348 soil properties and treatments (Table 2). The maximum increase in time to runoff for Marl  
349 and Loess soils was 14.41 and 37.10% respectively under PAM and BC treatments compared  
350 to control (Fig. 4). The experiments for Marl soil showed that BC and BC+PAM respectively  
351 decreased the time to runoff by 22.03 and 36.61% ( $P>0.05$ ), while PAM increased the time to  
352 runoff at a tune of 14.41% ( $P>0.05$ ). The mean change of BC, PAM and BC+PAM  
353 effectiveness in time to runoff of Loess soil were found with rate of +37.10, +12.90 and  
354 +12.90%, respectively (Fig. 4). The results indicated that treated soils of Marl and Loess did  
355 not cause a significant ( $P>0.05$ ) increase in time to runoff compared to the control (Table 2).  
356 The general trends were observed for effect of treatments on the time to runoff from  
357 maximum to minimum for the Marl soil was as BC>Control>PAM>BC+PAM and by instead  
358 of for the Loess soil was as PAM>BC=BC+PAM>Control.

359 For our study, it could be concluded that the ineffectiveness of BC and BC+PAM in delaying  
360 the time to runoff at Marl soil is related to the physical, chemical, and mineralogical  
361 properties of this soil. It also supposed that the plot scale ( $0.25\text{ m}^2$ ) and the short time  
362 between soil amendment application and rainfall simulation (48 h) might be affected our  
363 results. To verify the obtained results, it is suggested to use larger plots and longer span time  
364 in the future research. It is also hypothesized that a longer time of BC application before the  
365 rainfall event (e.g., more than one week) will help complete the interactions between the soil  
366 and amendments in the Marl soil with a silty clay loam. Our observation also verified that the  
367 fresh BC was hydrophobic. In addition, the high viscosity that caused by study amendments  
368 is another reason to their low- or ineffectiveness in delaying time to runoff. On the other  
369 hand, the longer time to runoff in the study treatments for Loess soil could be related to lack  
370 of clay, which facilitates better interaction between BC and PAM with the soil particles. In



371 this line, Yakupoglu et al. (2019) showed that PAM did not significantly ( $P>0.05$ ) delay the  
372 runoff generation in comparison to the control treatment for different soil aggregate sizes and  
373 sequential rainfall events in Turkey. They conclude that the PAM could penetrate to the  
374 aggregate soils and improve the structure. However, antecedent soil moisture was reported as  
375 a potential factor that could modify the soil aggregate stability. So that, the activation of the  
376 runoff and soil loss after the sequential rainfall was higher than after the first rainfall.

377 Similar to our results, Marete et al. (2013) showed that the addition of PAM to the clay loam  
378 soil neither reduced the total runoff or time to runoff initiation significantly during the first  
379 rainfall application nor for the subsequent three rainfall applications. Whilst, Sadeghi et al.  
380 (2016a) reported the significant ( $p=0.014$ ) effect of BC amendment in increasing the time to  
381 runoff compared with untreated plots under lab experiments for a sandy clay loam soil  
382 collected from rangelands of the Alborz Mountains, northern Iran. The rates of +71.73% and  
383 +55.10% of mean change in time to runoff were found respectively for BC application at 48  
384 and 24 h before the simulation treatment compared with that reported for control condition.  
385 These different hydrological responses is related to the soil physical protection provided by BC  
386 against crusting and consequently infiltration increasing. In addition, Peng et al. (2019)  
387 reported the effective role of BC on delaying the time to runoff generated from a silt loam  
388 soil particularly when applied at a higher rate (i.e.,  $30 \text{ t ha}^{-1}$ ). They concluded that the  
389 saturated hydraulic conductivity ( $k_{\text{sat}}$ ) of soil is one of the main factors affecting the time to  
390 runoff generation. Towards to un-similar results obtained by BC for different conditions,  
391 Olsson et al. (2019) and Sadeghi et al. (2020) also concluded that BC is a land management  
392 technique of high potential, but controversial. Sadeghi et al. (2020) related the reduction in  
393 the time to runoff generation to the physical adhesion of the soil surface, the salts existent,  
394 and nature of the material that protected the Marl and Loess soil mass.

395

### 396 3.1.2. Runoff coefficient

397 The results presented in Fig. 4 showed that BC had increasing effect on runoff coefficient for  
398 both Marl (29.18%) and Loess (5.11%) soils. While, the changes in runoff coefficient were as  
399 -2.47 and -13.67% for Marl and Loess soils for PAM treatment. The combined BC and PAM  
400 treatment also increased the runoff coefficient from 38.66 (control) to 47.29% for Marl soil  
401 and from 46.42 (control) to 54.70% for Loess soil. The minimum runoff coefficient appeared  
402 in PAM application for Marl and Loess as 37.70 and 40.07%, respectively. The obtained  
403 trend for runoff coefficient was observed as PAM<Control<BC+PAM<BC for Marl soil and  
404 as PAM<Control<BC<BC+PAM for Loess soil. Similar to the time to runoff results, here is  
405 also the higher efficacy of PAM rather than BC and BC+PAM treatments was attested. Then,  
406 it is expected to follow similar mechanisms. While, it is hypothesized that the addition of BC  
407 to soil especially in combination with PAM due to its alkaline nature caused a viscosity on  
408 the sensitive soil surfaces of Marl and Loess and intensified the runoff coefficient. The  
409 effectiveness of PAM and ineffectiveness of other two treatments compared to control plots  
410 in decreasing runoff coefficient could be dependent on the soil physic and chemistry. Both  
411 study soils suffer from existing high amount of silt and some chemical materials that are anti-  
412 aggregations (Catt, 2001; Soufi and Isaie, 2007; Ajami et al., 2016; Maleki et al., 2018). In  
413 addition, the constant conditions of rainfall intensity, time span between treatment application  
414 and simulation, plot scale and method of treatment application could be considered as  
415 limiting factors. For example, it is supposed that if the treatment will be mixed with the top  
416 surface soils, better results will be obtained. This could be examined by future research.

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

421 (2016) and Farhoodi et al. (2019) reported positive effects of BC on runoff coefficient  
422 respectively for arable sandy loam, loam clay sandy and clay soils of Iran. Despite BC  
423 potential to reduce runoff coefficient for some cases and its widespread land application, the  
424 uncertainties outlined on its negative effect on runoff coefficient under Marl and Loess soils  
425 of northern Iran is a serious concern. It is assumed that the properties of BC strongly depend  
426 on the raw materials, the conditions of production, soil properties and climatic  
427 characterizations. Wei et al. (2014) stated that the PAM application with rates of 0.5, 1.0, and  
428 2.0 g m<sup>-2</sup> increased the runoff coefficient as compared with control treatment of Loess soils in  
429 China.

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

437 The results also showed that the conservation treatments had no significant effect (P>0.05) on  
438 runoff coefficient changes compared to the control treatment. Besides, the reductions of mean  
439 soil pore size from 0.07 to 0.046 mm<sup>2</sup> and soil tensile strength from 466 to 164 kPa due to  
440 BC application (5% w/w) were recorded by Devereux et al. (2012) and Zong et al. (2016). In  
441 addition, Lee et al. (2015) attributed the increased runoff from loam soils subjected to BC,  
442 PAM and BC+PAM amendments to clogging soil pore. Studies showed that the addition of  
443 PAM to the clay loam soil did not reduce the total runoff significantly under different  
444 conditions (Vacher et al., 2003; Marete et al., 2013). Wang et al. (2011) also noted that the 2  
445 g m<sup>-2</sup> PAM application increased runoff as compared to the control. The same results were

446 obtained by Lee et al. (2015) who found that the runoff increased by 14.8, 22.9, and 23.2%,  
447 respectively in the plots amended with BC, PAM, and BC+PAM, compared to the control.  
448 They concluded that the increases of runoff were mainly resulted from PAM addition.

449

### 450 **3.1.3. Infiltration**

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

471 affectability from study treatments (Hseu et al., 2014; Alkhasha et al., 2018) that is not  
472 measured in this work.

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

#### 486 **Fig. 4**

487

### 488 **3.2. Water quality components**

#### 489 **3.2.1. pH**

490 Fig. 5 shows pH of runoff laden sediments collected from plots treated by different  
491 amendments for two study soils with non-significant differences ( $P>0.05$ ). PAM applications  
492 partially lowered the pH compared to the control plot. In addition, the pH values of runoff  
493 generated from BC and BC+PAM little increased compared to control. *The fitted models  
494 between runoff amount and pH values showed a fairly strong coefficient of determination  
495 ( $R^2 > 0.55$ ) under all treatments particularly in Loess soil (Fig. 6).* The increase in the soil pH

496 of the Marl and Loess soils from BC application might have also amplified soil dispersal  
497 (e.g., Novak et al., 2009; Lee et al., 2015) leading to a decline in infiltration compared with  
498 the PAM treatment that had no increasing effect on the soil pH (Table 2 and Fig. 5).  
499 The pH increase could be subject to the both primary of study soil pH and the raw materials  
500 used for BC production. For Marl and Loess soils, the initial soil pH, was respectively about  
501 7.68 and 8.2. In addition, the pH difference between control and treated runoff by BC is very  
502 small and non-significant ( $P>0.11$ ). Our findings showed similar trends established in various  
503 studies (e.g., Novak et al., 2009; Biederman et al., 2013; Lee et al., 2015) involving  
504 application of BC in increasing soil pH. The alkaline nature of BC, likely having a liming  
505 influence in the soils. For instance, Lu et al. (2012) reported that incorporation of sludge BC  
506 increased soil pH due to the alkalinity of the sludge. Blanco-Canqui (2019) through a review  
507 of relationship between BC and water quality concluded that the BC effect on water quality  
508 was depended on the BC feedstock, pyrolysis temperature, application amount, time after  
509 application, and its co-application with other amendments. Besides, pH of 11.02, 6.42, 6.60,  
510 6.17 and 6.62 were reported for BC, loam soil-control, BC treated soil, PAM treated soil, and  
511 BC+PAM treated soil by Lee et al. (2015). They conducted the chemical analysis after an 11-  
512 month erosion experiment and the results showed that the BC and PAM application resulted  
513 in significant higher soil pH.

514

515 **Fig. 5**

516 **Fig. 6**

517

### 518 **3.2.2. Electrical conductivity (EC)**

519 The BC and BC+PAM applications significantly ( $P<0.05$ ) increased the runoff EC of the two  
520 tested soils (Fig. 7). Since the main target of application of soil amendments is rehabilitation

521 of degraded soils and preparation of the appropriate bed for vegetation growth, providing  
522 information about the EC variation due to application of amendment is essential. Butnan et al.  
523 (2015) mentioned that the BC application leads to releasing basic cations into the soil and  
524 consequently results in increasing EC.

525 PAM alone did not increase EC of the released runoff. At both Marl and Loess soils, there  
526 was no differences between control and PAM, and no differences between BC and BC+PAM  
527 treatments (Table 3). The runoff EC for control, BC, PAM and BC+PAM were respectively  
528  $492\pm 25$ ,  $2410\pm 652$ ,  $491\pm 37$ , and  $2386\pm 255$   $\mu\text{S cm}^{-1}$  for Marl soil; and  $466\pm 23$ ,  $3244\pm 418$ ,  
529  $453\pm 17$  and  $3082\pm 400$   $\mu\text{S cm}^{-1}$  for Loess soil. The high value of coefficient of determination  
530 ( $R^2 > 0.87$ ) were observed between runoff volume and EC for all treatments except PAM at  
531 Marl soil (Fig. 8). The obtained results for all treatments except PAM assessed the ability of  
532 the obtained models to predict or explain the EC in the regression setting. The increase in EC  
533 might be corresponded to the dissolution of BC in the water. In our study, PAM did not  
534 increased the EC that is in consisted with Tafti et al. (2016) finding. Sadeghi et al. (2020)  
535 proved the negative effects of BC on water quality parameters and reported an EC increasing  
536 in runoff after BC application.

537

538 **Fig. 7**

539 **Fig. 8**

540 **Table 3**

541

### 542 **3.3. Erosion components**

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

545 **Table 4**

546

547 **3.3.1. Soil loss and sediment yield**

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

552 The application of BC (3.38-78.35%) and PAM (14.87-36.45%) reduced the sediment yield  
553 for both studied soils of this research ( $P>0.05$ ). Besides, BC+PAM increased the sediment  
554 yield (5.07%) for Marl soil and reduced the sediment yield (8.31%) for Loess soil  
555 ( $P>0.05$ ). Total sediment yield was lowest for PAM (5.80 g l<sup>-1</sup>), and highest for BC+PAM  
556 (7.15 g l<sup>-1</sup>) for Marl soil. The sediment yield induced from BC+PAM treatment was greater  
557 than control (6.81 g l<sup>-1</sup>) indicating negative effects of BC+PAM treatment for Marl soil  
558 conservation. However, all treatments decreased the sediment yield for Loess soil compared  
559 with control, so that the lowest and the highest value were attributed to BC (2.07 g l<sup>-1</sup>) and  
560 control (9.56 g l<sup>-1</sup>), respectively (Table 4 and Fig. 9). The results verified different  
561 mechanisms of individual and combined applications of BC and PAM on the soil loss and  
562 sediment. It is hypothesized that the obtained minor positive effects of adding individual and  
563 combined BC and PAM in Loess soil and only individual BC and PAM in Marl soil provided  
564 by their effects on the particles flocculation and aggregate stabilization. While, the adverse  
565 effect of BC+PAM for Marl soil could be interpreted by synergy impact of hydrophobicity  
566 caused by BC and PAM, simultaneously as well as the constructional nature, high deposits of  
567 silt and low clay of Marl soil. Existence of calcium carbonate, gypsum, anhydrite and salt in  
568 this soil also could help to this negative effect. In addition, in the present study, only BC  
569 powder and anionic PAM were used. It is also supposed that using different types of these  
570 amendments (e.g., different particle sizes of BC, powder type of PAM or its cationic type)



571 might have different impacts. Similar variations in mechanisms of BC and PAM were  
572 displayed by other researchers, too. For instance, Wang et al. (2011) indicated that the PAM  
573 application did not prevent the soil erosion. Mbagwu and Piccolo (1997) and Bayabil et al.  
574 (2015) have found that BC increased the soil macro-aggregate stability by 20-130%; depends  
575 on soil texture, clay mineralogy, as well as elemental constituents of amendments. Lee et al.  
576 (2015) attributed the decrease in soil loss to clay flocculation and aggregate stabilization  
577 made by PAM, and water adsorption capacity provided by BC. Their finding verified a  
578 maximum reduction of 19.9% in soil loss due to application of BC as compared to that of the  
579 control. Another potential explanation for the fact was that the BC cations and soil particles  
580 were bridged by trap water molecules under Coulombic and van der Waals forces thereby  
581 contributed to soil loss and sediment reduction. Blanco-Canqui et al. (2019) also reported that  
582 the BC application reduces soil loss by 11 to 78% indicating the high its variability. The  
583 reduction benefit of BC was differently reported by Sadeghi et al. (2020) under field  
584 experimental circumstances.

### 585 **Fig. 9**

586

#### 587 **3.3.2. Splash erosion**

588 BC and PAM in comparison with control reduced the different type of splash erosion  
589 including up, down and net splash erosions of Marl and Loess soils (Fig. 10). Our findings  
590 showed that PAM, BC and BC+PAM respectively were the best for up, down and net splash  
591 erosions control for the Marl soil, even if other treatments were also efficient. The non-  
592 significant ( $P>0.05$ ) effect of study treatments ranged from -26.18 (PAM; Net splash erosion)  
593 to 91.03% (BC+PAM; Net splash erosion). In addition, for Loess soil, the effective  
594 treatments were set as BC, BC, and PAM for up, down and net splash erosions control,  
595 respectively. The non-significant ( $P>0.05$ ) effect of the studied treatments on Loess soil

596 ranged from 13.69 to 72.50% associated with BC+PAM and PAM respectively for up and net  
597 splash erosion control (Fig. 10). Totally, splash erosion variability from BC and PAM is not a  
598 well-known, though its relevance and importance is often highlighted in the literature.

599 The reduction in the disintegration of soil particles from the bulk was measured by Hseu et al.  
600 (2014) for the mudstone formation of Taiwan. Moreover, the porosity (4-27%) and soil  
601 aggregate size (0.59-0.94 mm), as major determinant factors for the soil structure, increased  
602 after 168 days of BC application (Hseu et al., 2014). According to Bayabil et al. (2015)  
603 reports, BC bonds with soil surfaces mineral through carboxylic and phenolic functional  
604 groups, hence, improves the soil structural aggregation and stability. The atomic ratios of  
605 hydrogen:carbon (H:C) and oxygen:carbon (O:C) of used BC are another variables could  
606 affect the BC efficiency on the soil erosion control. Because they are indicative of the bonding  
607 arrangement and polarity (Sun et al., 2017). They are also correlated with the degree of  
608 thermochemical alteration during BC pyrolysis. Although in the present study, they are not  
609 calculated and it is suggested to measure for future soil erosion and water conservation  
610 studies. Sun et al. (2017) measured the H:C and O:C ratios for 60 BC types and their primary  
611 raw materials. They concluded that the raw materials and BCs (produced at 500 °C)  
612 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  
613 and 0 to 0.27 for O:C ratio.

614 Lee et al. (2015) also denoted that soil particle detachment could be eliminated using BC  
615 application due to absorption of raindrop energy or buffering on soil surface. Recently,  
616 Yakupoglu et al. (2019) showed that PAM reduced soil transported by splash considerably  
617 due to its charge density and molecular weight. Briefly, we showed that during the rainfall  
618 simulation, the resistance of treated soils with BC and PAM against erosion by raindrop  
619 splash increased in comparison with control soils. It was observed that the dissolved  
620 molecules of PAM were partially absorbed on the soil particles and partly enhanced the

621 aggregate stability leading to decreasing in splash rates during the rainfall event. The results  
622 were in agreement with the previous studies (e.g. Sadeghi et al., 2016c; Sadeghi et al., 2020)  
623 which confirmed the conservation effects of PAM on reducing net, upward and downward-  
624 splash erosion of the silty loam soil.

625

626

### Fig. 10

627

#### 628 4. Conclusion

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

646 recommended as complementary **research** to be considered in the future studies to find the  
647 most effective and applicable technology for the optimal use of the soil resources.

648

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659

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902

## 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 <sub>2</sub> O	1.852	1.870
MgO	1.563	2.787
Al <sub>2</sub> O <sub>3</sub>	2.017	3.377
SiO <sub>2</sub>	9.602	15.502
P <sub>2</sub> O <sub>5</sub>	0.418	0.604
SO <sub>3</sub>	7.087	8.592
K <sub>2</sub> O	10.021	11.007
CaO	10.93	18.578
TiO <sub>2</sub>	0.191	0.306
MnO	0.031	0.040
Fe <sub>2</sub> O <sub>3</sub>	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

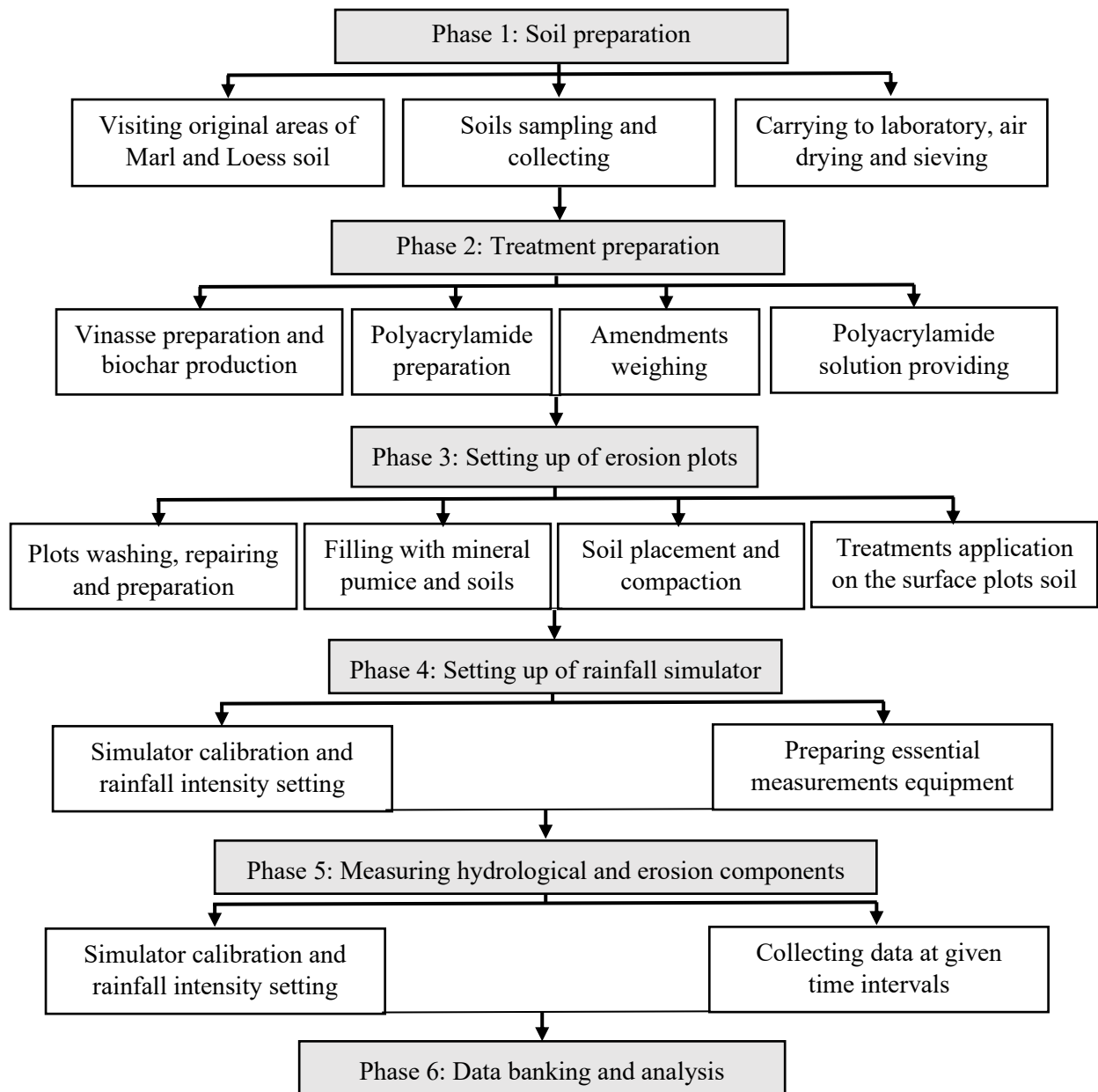
Runoff component	Soil Type	Treatment	Mean	Standard Deviation
Time to runoff (s)	Marl	Control	196.67	82.19
		BC	225.00	15.90
		PAM	153.33	47.32
		BC+PAM	124.67	20.74
	Loess	Control	103.33	30.64
		BC	116.67	26.25
		PAM	141.67	29.53
		BC+PAM	116.67	33.99
Runoff coefficient (%)	Marl	Control	38.66	22.44
		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 <sup>-1</sup> )	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



**Fig. 1**



**a**

**b**



**c**

**d**

**e**

**f**

**Fig. 2**



Fig. 3

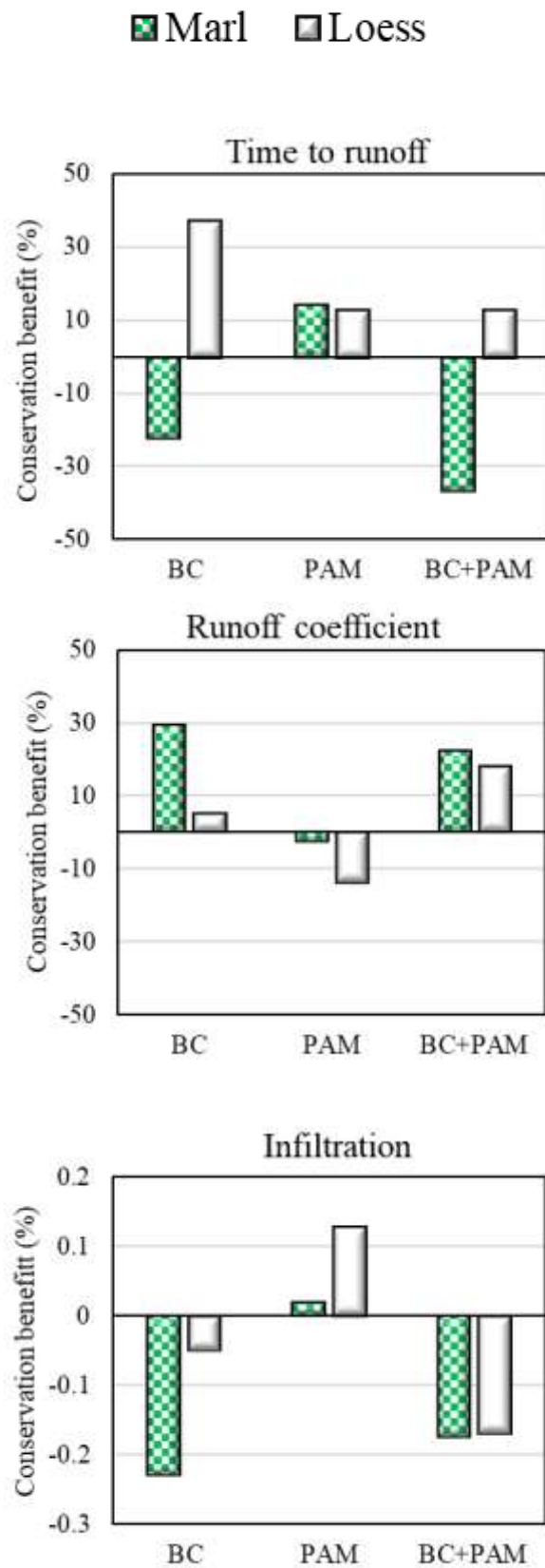


Fig. 4

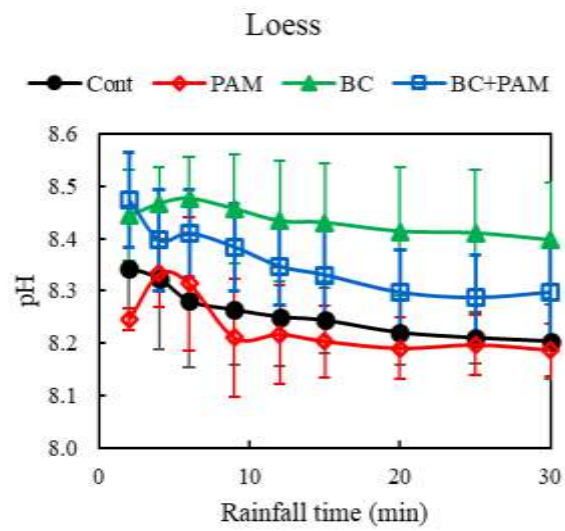
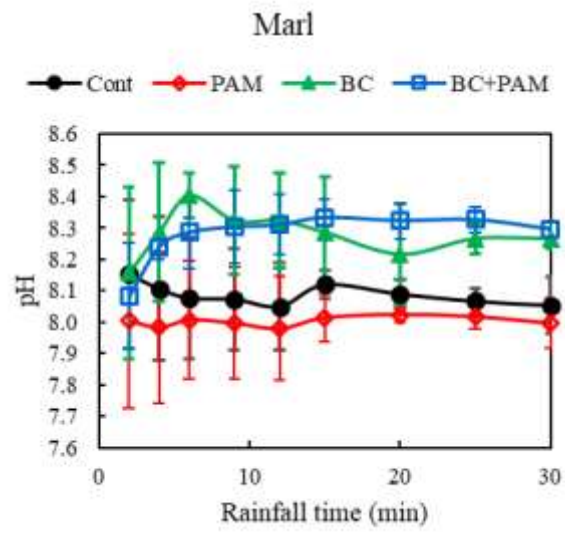


Fig. 5



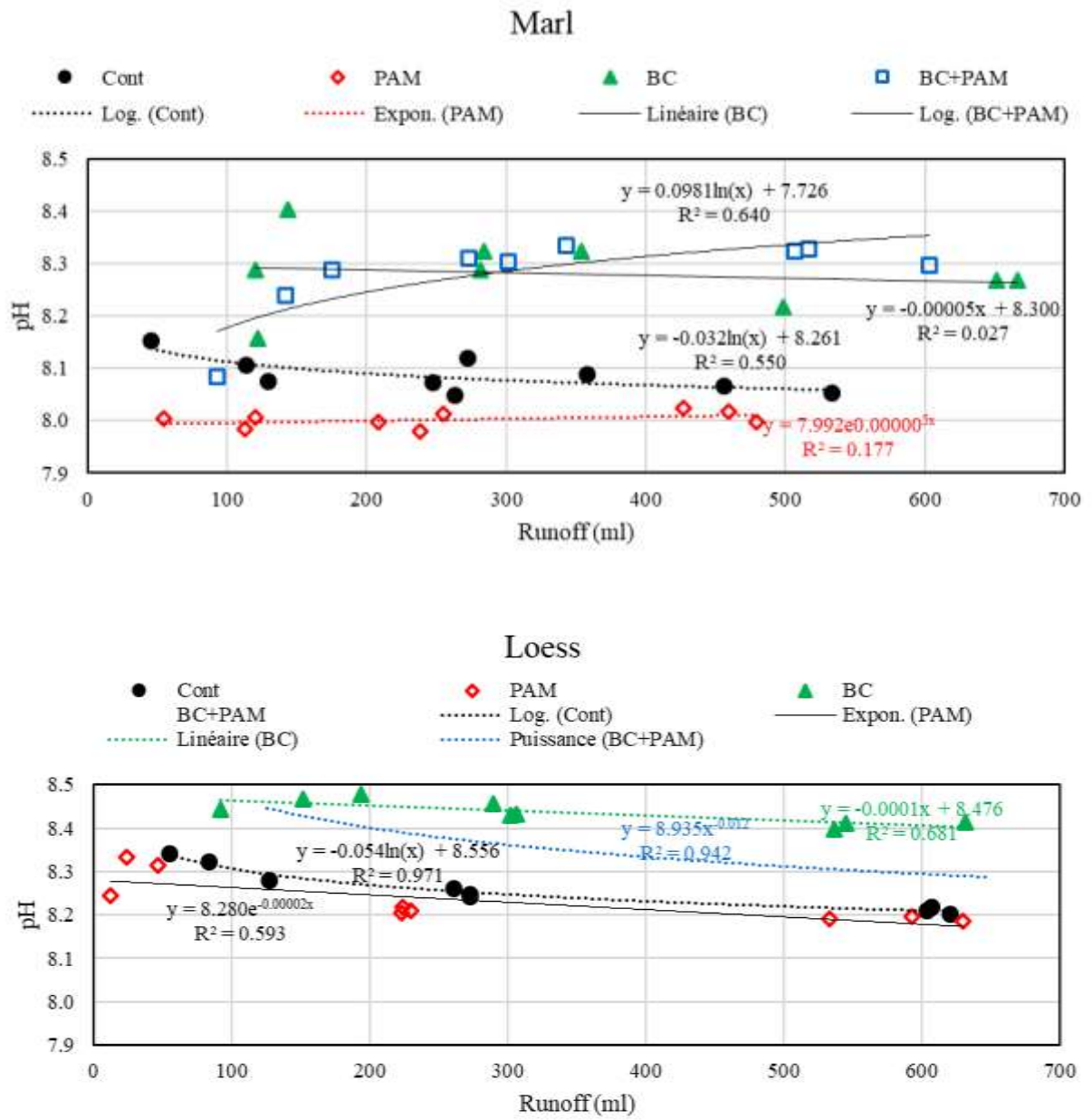
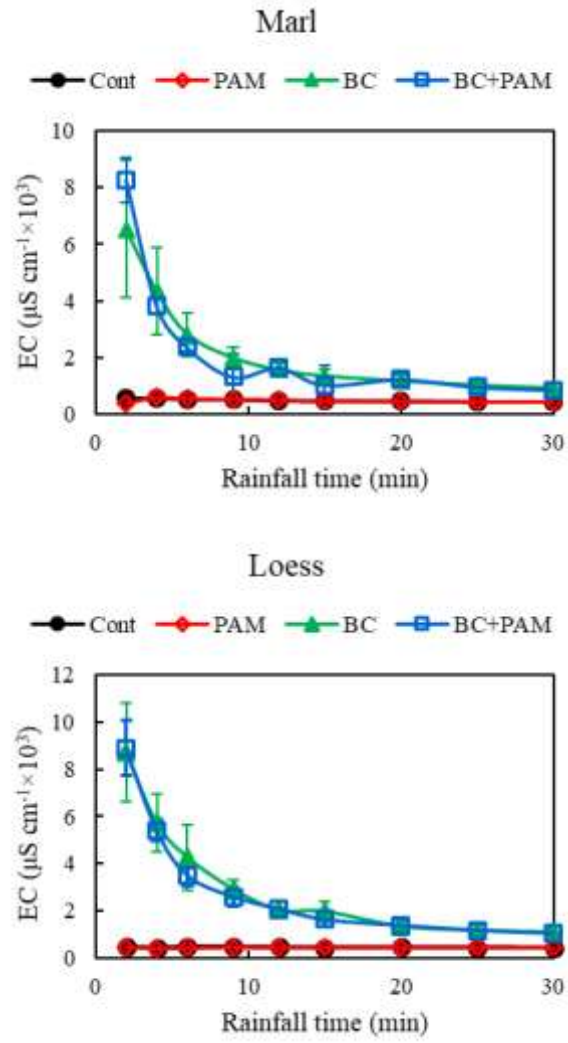


Fig. 6



**Fig. 7**

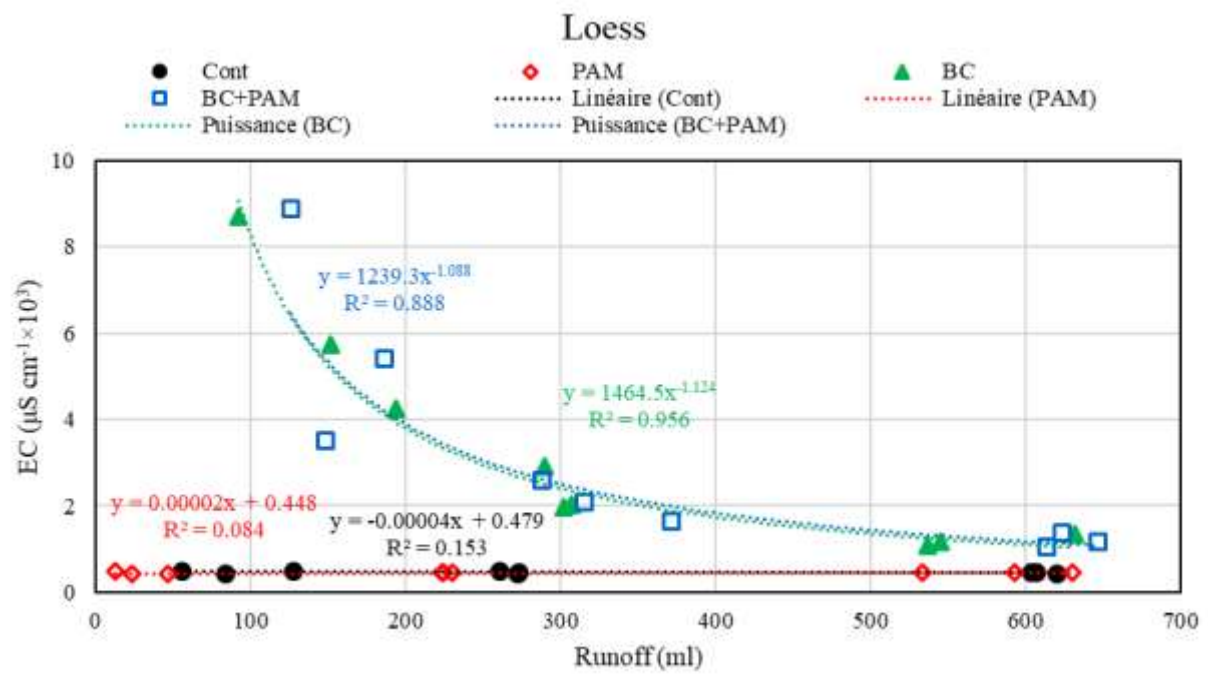
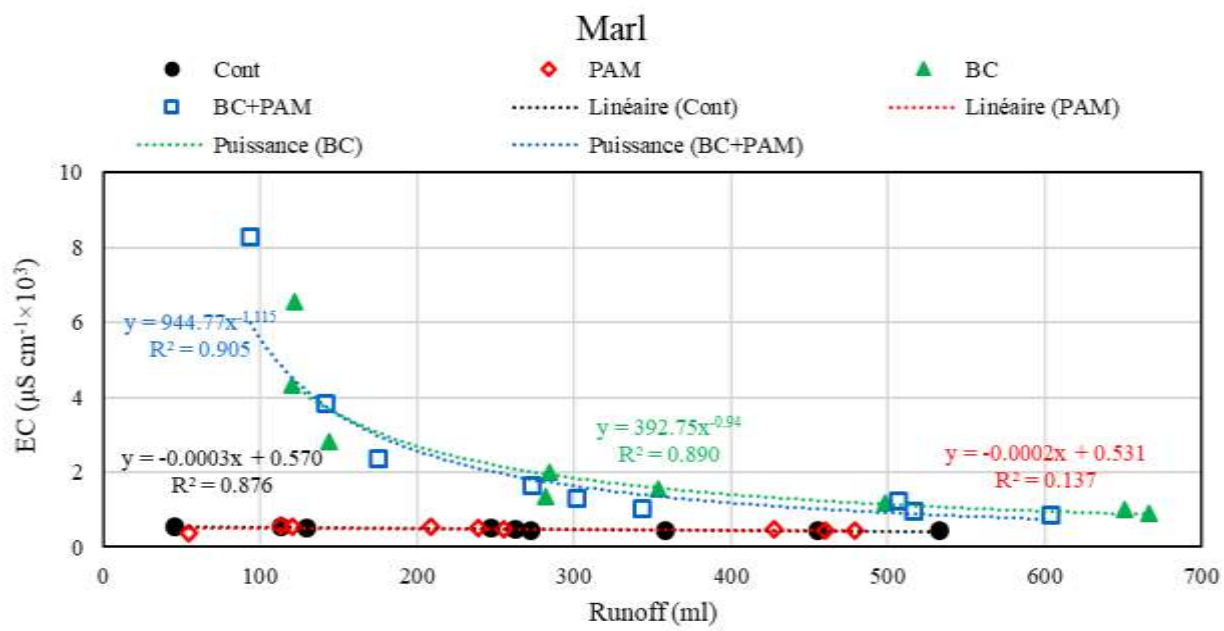


Fig. 8

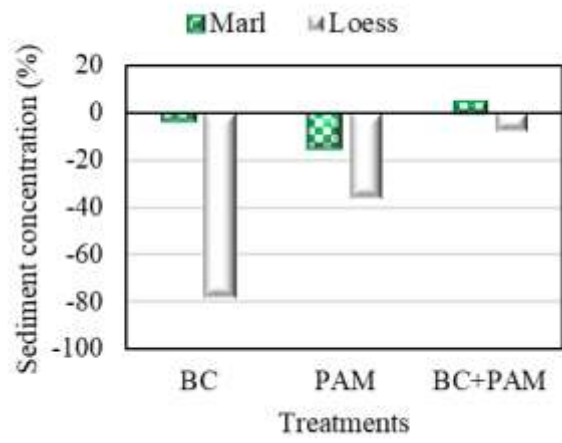
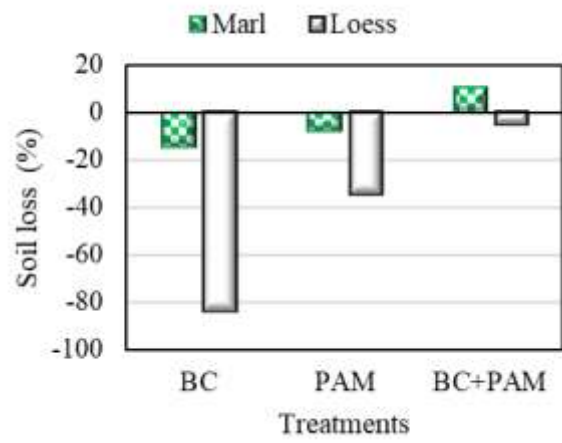
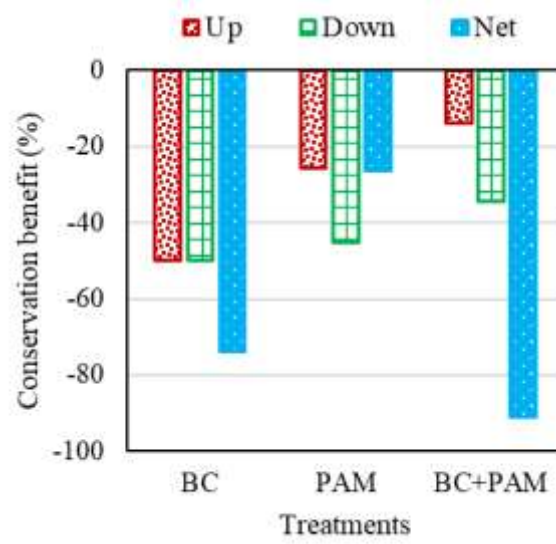
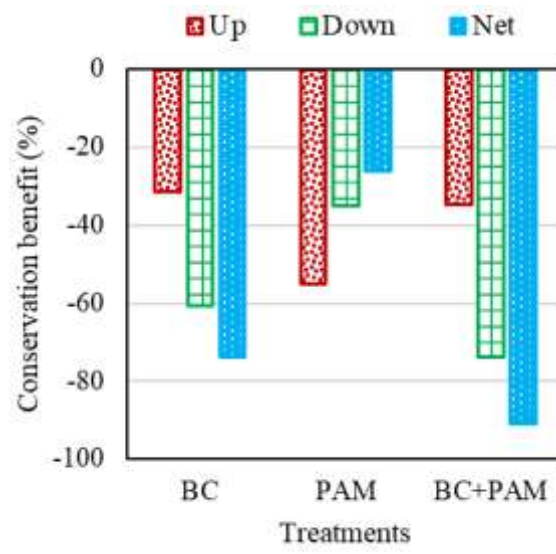


Fig. 9



**Fig. 10**