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Effectiveness of Polyacrylamide in Reducing Runoff and Soil Loss under Consecutive Rainfall Storms

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Abstract: The use of anionic polyacrylamide (PAM) as a soil conditioner could help prevent soil loss by water. In this study, we determined the effective granular PAM rate that best reduces runoff and soil loss from Oxisols. Furthermore, the effectiveness of the selected PAM rate was tested by applying it in a mixture with gypsum (G) or lime (L). The study was conducted in two phases: (i) Dry PAM rates of 0 (C), 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), and 60 kg ha^{-1} (P60) were applied onto soil surface and run for six consecutive rainfall storms of 70 mm h^{-1} intensity for 1 h duration, and the effective PAM rate was selected; and (ii) G (4 t ha^{-1}) or L (2 t ha^{-1}) were applied alone or mixed with the selected PAM rate. The P20 was found to be effective in reducing runoff in the beginning while P40 and P60 were more effective starting from the third storm through the end of the consecutive storms, but with no statistically significant difference between P40 and P60. Hence, P40 was selected as the most suitable rate for the given test soil and rainfall pattern. On the other hand, the mixed application of P40 with G or L increased infiltration rate (IR) in the first two storms through improving soil solution viscosity. However, effectiveness of the mixtures had diminished by various degrees as rain progressed, as compared to P40 alone, which could be attributed to the rate and properties of G and L. In conclusion, the variation in effectiveness of PAM rates in reducing runoff with storm duration could indicate that the effective rates shall be selected based on the climatic region in that lower rates for the short rains or higher rates for elongated rains. Moreover, combined application of PAM with L could offer a good option to both fairly reduce soil erosion and improve land productivity especially in acidic soils like Oxisols, which requires further field verification.

Keywords: polyacrylamide; gypsum; lime; runoff; soil loss; dryland

1. Introduction

Soil erosion by water is the most threatening global problem causing adverse on- and off-site consequences, such as the depletion of soil fertility [1–3], siltation of downstream reservoirs [4–6], loss of vital ecosystem services, and associated economic costs [7]. Low soil fertility due to the removal of organic matter rich surface soil by erosion and exposure of lower soil layers causes nutrient deficits and physical hindrance to root growth, leading to reduced soil productivity [8]. However, this effect of erosion on soil productivity is a slow process and might not be noticed until crop production is no longer economically viable [9]. As a result, soil erosion has become a major threat to food security, particularly for developing countries where livelihoods predominantly depend on agriculture [2,10–15]. Hence, soil and water conservation are essential for sustaining food production and preserving the environment [16].

The major causes of soil erosion are the physical disintegration and dispersion of surface soil aggregates by the impact energy of raindrops [17,18] and the physico-chemical dispersion and migration of soil clays with the infiltrating water into the soil, thereby clogging the conducting pores [19–21], leading to crust formation, decreased infiltration, and increased runoff and soil loss [21–23]. Soil erosion can be prevented by using physical and biological measures, or through conventional management practices such as mulching, growing cover crops, etc. An alternative practice is the modification of soil properties through the application of chemical amendments to the soil, such as polyacrylamide (PAM) [22] to decrease aggregate disintegration.

PAM is a water-soluble, organic anionic polymer having a long molecule of identical atom chains held together by covalent bonds [24] that form bridges with the soil particles through cations in soil solution [25]. PAM has proved to be superior to other polymers in controlling erosion [26] and is also used to improve soil physical properties [25]. PAM remains effective in reducing soil loss by limiting the physical disintegration of aggregates caused due to water drop impact [27] by adsorption to the soil aggregates and increasing cohesion among soil particles [28], thus increasing the resistance of aggregates to the direct impact of raindrops or dragging force by runoff. Factors like soil characteristics, water quality, and PAM properties such as charge density and molecular weight play important roles in the adsorption of PAM [25]. PAM can stabilize an existing soil structure by preserving pervious pore structure during the surface seals formation [29], but is unable to remediate a poor soil structure [30]. PAM is infinitely soluble in water but dissolves very slowly [31]. It is more readily adsorbed by the water of a higher electrolyte concentration than by water with lower electrolyte concentration [32]. Nevertheless, the addition of dissolved PAM may have some negative effects, such as enhancing water viscosity at the beginning, which in turn could lead to a decrease in infiltration rate (IR) and increased runoff, although it may decrease soil erosion [28,33]. Furthermore, the high application rates required for effective erosion control and the large volume of water required for effective dissolution are the two major obstacles constraining the usage of PAM in agriculture [34].

Although anionic PAM is the most effective polymeric soil amendment to control erosion [35], its effectiveness can be enhanced by introducing a source of electrolyte that can create a cation bridge and help the polymer to adsorb to the soil [26]. The introduction of electrolyte (such as Ca^{2+}) at the soil surface reduces chemical dispersion and migration of clay particles by strengthening the bonds between primary soil particles, thus reducing seal formation [31,36]. Electrolytes are typically introduced in the form of gypsum and lime. The increase in the electrolyte concentration in soil replaces exchangeable Sodium (Na^{+}) ions from the exchange complex with dissolved Calcium (Ca^{2+}) ions. In addition, it decreases clay dispersion and surface sealing [36], enhances soil structure, increases infiltration rate (IR), and decreases runoff and sediment loss [37]. Furthermore, the effectiveness of PAM application depends primarily on the soil type and percentage of clay in the soil [35,38].

Many studies have been conducted to determine the effective rates of anionic PAM that can reduce runoff and soil loss through soil structure stabilization [39,40]. Most of these studies have shown that application rates of 10–20 kg ha^{-1} were effective in stabilizing the surface structure and decreasing runoff and soil erosion [40]. In earlier times, Gabriels et al. [41] found that applying 38 kg ha^{-1} of anionic PAM to soil surface resulted in increased IR and reduced runoff while other researchers [25,42,43] suggested the use of 20 kg ha^{-1} PAM as an effective and economical application rate. However, these effective PAM rates in most of the studies were determined using a maximum of three simulated rainfall storms (<250 mm rainfall), which may represent dry land regions.

For example, Lado et al. [39] evaluated the effectiveness of granular PAM at rates of 0, 25, 50, and 100 kg ha^{-1} to reduce post-fire erosion in a Calcic Regosol affected by different fire conditions using three consecutive rainfall storms of 80 mm depth each with an intensity of 47 mm h^{-1}. They found that the application of 50 kg ha^{-1} granular PAM increased runoff during the first storm due to increased viscosity of runoff. However, this rate was more effective in reducing soil loss during the three storms in unburnt and moderately burnt soils, with a total reduction of 42% and 34%, respectively. In addition, Abrol et al. [40] also evaluated the effect of the application rate of granular PAM (0, 5, 10, and 20 kg ha^{-1}) on IR as a function of cumulative rainfall in silt loam soil using 2-hour simulated rainstorm at rainfall intensity of 37 mm h^{-1}. That study showed that the application rate of 10 kg ha^{-1} was more effective in increasing IR and reducing erosion.

In both studies, the higher PAM rates, 100 kg ha^{-1} [39] and 20 kg ha^{-1} [38], were less effective, as compared to lower and medium rates. This could be that the amount of rainfall applied in these storms was insufficient to completely dissolve PAM at higher rates, as higher rates require a large volume of water for effective dissolution [34]. This suggests the importance of applying sufficient rainfall such that all the applied PAM gets fully dissolved to effectively act on soil aggregate stabilization and then monitoring the effect of PAM application rates on IR, runoff, and soil loss. PAM effectiveness is, therefore, believed to be strongly influenced by the rainfall pattern that a certain soil is subjected to and requires study under consecutive rainfall storms of high intensity. Hence, treating a test soil with different PAM rates, exposing it to consecutive rainfall storms of high intensity, which may represent humid and sub-humid regions, and determining the effective PAM rate that produces better results in terms of reducing runoff and soil loss is the best way forward. Moreover, applying PAM mixed with some source of electrolytes (e.g., gypsum and lime) at the effective rate and exposing it to consecutive rainfall storms will help us to understand whether the mixture of PAM and electrolytes can further enhance PAM effectiveness for a given test soil under consecutive storms.

The purpose of this study was, therefore, to evaluate the effectiveness of PAM rates (0, 20, 40, 60 kg ha^{-1}) in increasing IR and reducing runoff and soil loss when applied to a test soil (acidic Oxisol) and subjected to consecutive rainfall storms. The two main objectives were:

(i) To determine the effective granular PAM rate that increases IR and reduces runoff and soil loss under consecutive rainfall storms; and
(ii) To verify whether the effectiveness of the selected rate can further be enhanced by applying it mixed with gypsum (4 t ha^{-1}) or lime (2 t ha^{-1}) as a source of electrolyte.

2. Materials and Methods

2.1. Experimental Setup and Materials

This experiment was conducted at Arid Land Research Center (ALRC) of Tottori University during January–March 2019. The test soil used for this experiment was acidic clay red soil (similar to Oxisols by US Taxonomy or Acrisols and Luvisols by FAO classification), one of the widely abundant soils in Japan. Small runoff boxes of dimensions 50-cm length, 30-cm width, and 7-cm depth were filled with soil (Figure 1). The boxes have two outlets for collecting surface runoff and percolating (infiltration) water. The amendments used were environmentally friendly, non-toxic anionic PAM (Superfloc A-110, granular powder, 10−12% hydrolysis, and 12 Mg mole^{-1} molecular weight), gypsum, and lime. Similar to most previous studies, we were interested in granular application not only due to its durability but also because the granular method of application improves handling and reduces costs compared with that of the fluid (solution) application [16,37].

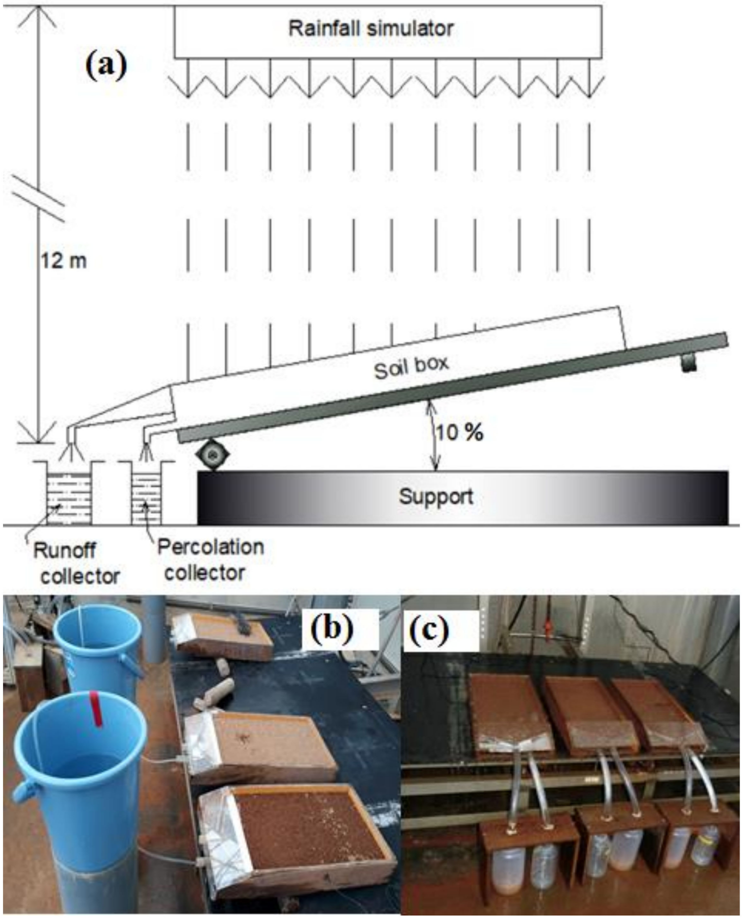

Figure 1. Experimental set-up showing (**a**) rainfall simulator, experimental soil box, and runoff and percolating water collector; (**b**) different treatments being saturated from below; and (**c**) runoff and percolating water collection during simulation.

The soil was air-dried, gently crushed, and sieved through a 5 mm sieve. Firstly, we packed gravel of 1–2 mm diameter up to a depth of 2 cm in the small runoff boxes to allow the percolation of infiltrated water. The sieved soil was then packed up to a depth of 3 cm in each box over the 2 cm layer of gravel, compacted to a bulk density of 1.2 g cm^{-3} using a wooden log, and finally, amendments were applied. PAM was applied onto the soil surface at a rate of 0 (C), 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), and 60 kg ha^{-1} (P60) in granular form. The entire PAM rates were then exposed to the six consecutive storms, runoff and soil loss were measured, and effective PAM rate was selected. Later, gypsum (G) at a rate of 4 t ha^{-1}, and lime (L) at a rate of 2 t ha^{-1} were applied alone or in mixture with the effective PAM rate selected above. Each amendment was applied (uniformly distributed) over the soil surface by hand. For the combined treatments of PAM mixed with gypsum or lime, first PAM alone was applied followed by the application of gypsum or lime.

2.2. Rainfall Simulation Procedure

A drip-type rainfall simulator facility with raindrop fall-height of 12 m, raindrop diameter of 3 mm, and rain kinetic energy of 29 J^{-1} m^{-2} mm^{-1} [44] at the ALRC, Tottori University, Japan was used in this study. The simulation was conducted in two phases: The first phase using four PAM rates (0, 20, 40, and 60 kg ha^{-1}) and the second phase using gypsum, lime, and effective PAM rate mixed with gypsum or lime. Out of the four rates, the effective PAM rate was selected based on the simulation results from the first phase.

In both phases, after all amendments were applied, the boxes were placed over the simulator tray in a horizontal position and saturated from below for 10 to 15 minutes with deionized water in order to facilitate the immediate measurement of infiltrating water during the first simulation. After saturation, the boxes were air-dried for 24 h prior to the start of the simulation. The simulator tray was set to a slope of 10%, and three soil-packed runoff boxes, with treatments assigned randomly, were positioned side-by-side on the sloped platform to allow simultaneous testing of different treatments. Boxes were then exposed to six consecutive rainstorms using tap water (EC= 0.07 dS m^{-1}). Rainfall intensity was 70 mm h^{-1} lasting for 1 h rainfall duration, and time interval between two consecutive rainstorms was two days (48 h). Although the rainfall intensity of 70 mm h^{-1} lasting for 1 h may not be common under natural conditions, globally large-magnitude events are assumed to be a dominant cause of soil erosion [45,46]. Initially, runoff boxes were covered with plastic covers, and after the rain intensity was stabilized, we removed the plastic covers and started recording the time taken to initiate runoff (TRO), the infiltrated water that come to the box outlet as sub subsurface flow, and runoff (Figure 1).

During each storm, runoff and infiltrating water were collected at every 10-min interval, throughout the 1-h storm duration, using temperature resistant graduated plastic bottles placed underneath the outlet at the bottom of the box. At the end of the simulation, the 10-min volume of runoff and infiltrated water was measured using a graduated cylinder. The runoff volumes were oven-dried at 105 °C using the temperature resistant plastic bottles, and the weights of sediments in the runoff were determined. Then, the total soil loss of a treatment was found by summing up the amount of sediments obtained from the oven dried 10-min runoff volume in the six consecutive storms. It is worth noting that the transfer of splashed particles from one box to the other during rainfall simulations might affect the results. However, for the rain simulator and intensity used in this study, the splash erosion was reported to be minimal [47]. Therefore, splash from the runoff boxes, which could be directly related to the rain intensity or erosivity, was not measured. The cumulative runoff and cumulative soil loss were subjected to statistical analysis using IBM SPSS Statistics version 22 software. The simulation datasets (cumulative runoff and soil loss) were tested for normality and found to be significantly different from the normal distribution; hence parametric statistical tests could not be used for this study. Therefore, the differences among the median cumulative runoff and soil loss were subjected to analysis of variance using the Kruskal–Wallis non-parametric test [48] at a significance level of 0.95 (α = 0.05).

2.3. Soil Physico-chemical Properties and Aggregate Stability Determination

Original soil properties and soil properties following the final rainfall storm were determined. Soil samples were collected from each treatment, dried, and used to determine the soil properties. Soil texture was determined for untreated soil samples using the hydrometer method [49]. The air-dried soil samples were used for the determination of electrical conductivity at 1:5 ratio, soil pH at 1:2.5 ratio, soil organic carbon with C/N coder apparatus, and cation exchange capacity (CEC) using atomic absorption spectroscopy (AAS) after extraction with ammonium acetate buffered at pH 7 (Table 1). The soil is characterized by clay texture (44.4%, 13.4%, and 42.2% for clay, silt, and sand, respectively) and with 3.6% organic matter content.

Table 1. Effect of treatments on soil properties. Different treatments are control (C), polyacrylamide (PAM) of 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), 60 kg ha^{-1} (P60), PAM of 40 kg ha^{-1} + gypsum (4t ha^{-1}) (P+G), gypsum (4t ha^{-1}) (G), lime (2t ha^{-1}) (L), and PAM of 40 kg ha^{-1} + Lime (2t ha^{-1}) (P+L).

Treatments	pH	EC (dS m^{-1})	CEC (cmol$_c$ kg^{-1})	NH_4OA_c Extractable Cations (cmol$_c$$^+$ kg^{-1})			
				Ca^{2+}	Mg^{2+}	K^+	Na^+
Untreated soil	4.84	0.05	16.35	10.83	4.40	0.71	0.41
C	4.86	0.05	14.69	9.52	4.20	0.62	0.35
P20	4.86	0.05	15.19	9.80	4.33	0.69	0.36
P40	5.03	0.05	15.15	9.88	4.29	0.59	0.39
P60	5.09	0.05	15.48	9.49	4.96	0.64	0.39
P40+G	5.11	0.08	17.78	11.03	6.00	0.57	0.18
G	4.85	0.12	16.18	10.93	4.50	0.56	0.19
L	6.75	0.37	19.23	13.52	4.80	0.67	0.24
P40+L	5.14	0.09	16.86	11.79	4.10	0.69	0.28

Aggregate (structure) stability with three replications (taken from upper 5 mm of the soil in each box) was determined using the modified high energy moisture characteristics (HEMC) method [38,50]. In this method, soil aggregates are wetted rapidly in a controlled manner, and a moisture content curve, at a matric potential range of 0–50 cm, corresponding to drainable pores of >60 µm, with small steps of 1–2 cm, was generated using a hanging water column. An index of aggregate stability or structural index (SI) was determined from differences among the water retention curves (differences in pore size distribution) of the treatments by using their specific water capacity curves. The volume of drainable pores and modal suction (matric potential at the peak of the specific water capacity curve corresponds to the most frequent pore size) were determined and SI was defined as the ratio of the volume of drainable pores to modal suction, and used to characterize soil aggregate and structure stability; the higher the value of SI, the higher the stability of samples [50].

3. Results

3.1. Effect of Treatments on Soil Properties

The effect of soil amendments on soil properties is presented in Table 1. Generally, the lime substantially increased the soil pH, EC, and CEC more than other treatments. However, this effect of lime was decreased when combined with PAM. Gypsum did not increase pH but slightly increased EC and CEC. This difference could probably be attributed to leaching of gypsum by the continued rainfall due to its high solubility.

3.2. Time to Runoff (TRO)

Time to runoff (TRO) for the different treatments is presented in Figure 2. During Storm 1, the shortest TRO i.e., 67% reduction was observed for higher PAM rates (P40 and P60), followed by 33% reduction for P20 and PAM associated treatments (i.e., P+G and P+L) while 33% increment was observed for gypsum treatment, compared with the control (Figure 2). For Storms 2 to 6, the runoff was initiated immediately after the start of rainfall.

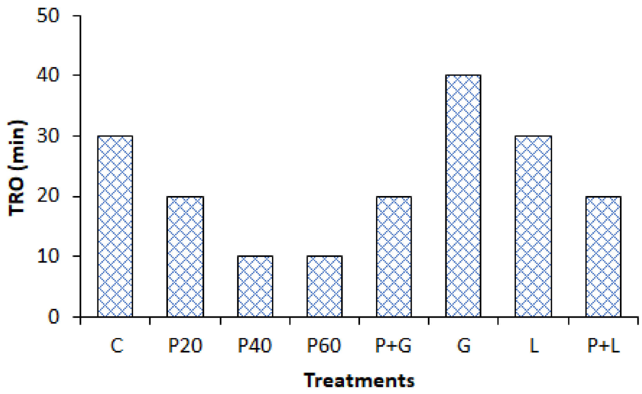

Figure 2. Effect of treatments on time to runoff (TRO) for control (C), PAM of 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), 60 kg ha^{-1} (P60), PAM of 40 kg ha^{-1} + gypsum (4 t ha^{-1}) (P+G), gypsum (4 t ha^{-1}) (G), lime (2 t ha^{-1}) (L), and PAM of 40 kg ha^{-1} + Lime (2 t ha^{-1}) (P+L).

3.3. *Effect of Polyacrylamide (PAM) Rates on Infiltration Rate (IR), Runoff, and Soil Loss*

IR, runoff, and soil loss measured from the fine texture Oxisol treated with PAM rates of 0, 20, 40, and 60 kg ha^{-1} and subjected to six consecutive rainstorms separated by drying periods are presented in Figure 3. At the beginning of Storm 1, compared with the control, IR for all PAM rates reduced by 4%, 24%, and 46% for P20, P40, and P60, respectively. However, as the rainfall continued from Storms 2 to 6, IR for all PAM rates increased by 61−147%, 63–268%, and 20–338% for P20, P40, and P60, respectively. Furthermore, IR for higher PAM rates slightly decreased during Storm 2, compared with IR during Storm 1. However, IR sharply increased during Storms 3 and 4 but decreased again during Storm 5 and 6 for the higher rates. IR values from P20 continuously decreased throughout the consecutive storms, however, the final infiltration rate (FIR) during Storm 6 increased by 61%, 182%, and 229% for P20, P40, and P60, respectively, compared with the control (Figure 3).

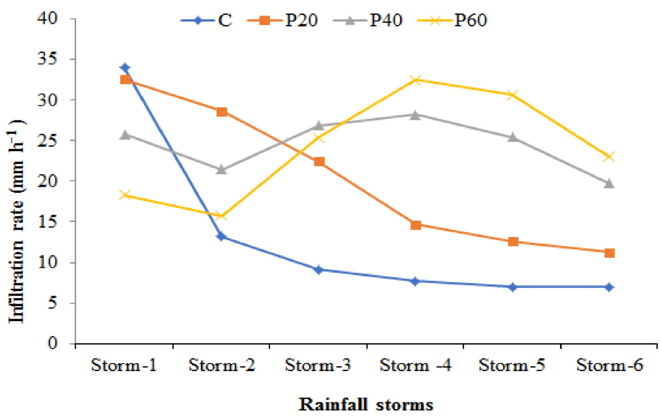

Figure 3. Effect of PAM rates on infiltration rate (mm h^{-1}). Each of the six storms had an average rainfall intensity of 70 mm h^{-1} for 1-h duration and 48-h drying period. The treatments were control (C), PAM of 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), and 60 kg ha^{-1} (P60).

Following the reduction in IR at different PAM rates, when compared with the control, cumulative runoff increased during Storm 1 by 5%, 28%, and 54% for P20, P40, and P60 rates, respectively. However, cumulative runoff decreased for all the rates later in the consecutive storms depending on the changes in IR (Figure 4a). During Storms 2 to 6, cumulative runoff reduced by 7–27%, 15–29%, and 5–40% for P20, P40, and P60, respectively. The cumulative runoff increased in the order P60 > P40 > P20 for Storms 1 and 2 and in the order C > P20 > P60 > P40 for Storms 4 to 6. Nevertheless, runoff from control was the lowest during Storm 1, but increased sharply during Storm 2, and was the highest of all treatments throughout the consecutive Storms 2 to 6 (Figure 4a). The total runoff from all the six consecutive storms decreased in the order of C > P20 > P60 > P40 (Table 2).

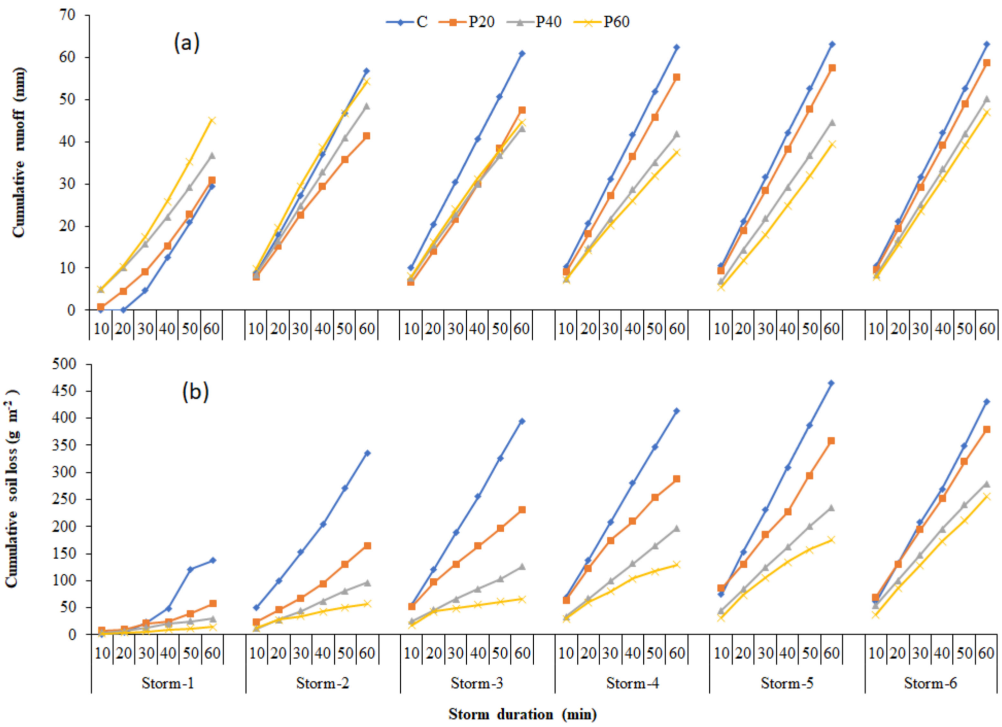

Figure 4. Effect of PAM rates on (**a**) cumulative runoff (mm) and (**b**) cumulative soil loss (g m^{-2}). Each of the six storms had an average rainfall intensity of 70 mm h^{-1} for 1-h duration and 48-h drying period interval. Data were collected at 10-min intervals in the 1-h rainfall duration. The treatments were control (C), PAM of 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), and 60 kg ha^{-1} (P60).

Table 2. Effect of PAM rates on total runoff and total soil loss with respective percent reduction (%) compared with control and cumulative median runoff and soil loss from the six storms. Different letters following treatments indicate a significant difference between treatments using the Kruskal-Wallis test (α = 0.05). The treatments were control (C), PAM of 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), and 60 kg ha^{-1} (P60).

Treatments	Runoff			Soil Loss		
	Total Runoff (mm)	Reduction in Total Runoff (%)	Cumulative Median Runoff (mm)	Total Soil Loss (g m^{-2})	Reduction in Total Soil Loss (%)	Cumulative Median Soil Loss (g m^{-2})
C	336		62 ^{a}	2152		407 ^{a}
P20	292	13	52 ^{b}	1491	31	280 ^{b}
P40	265	21	45 ^{b}	919	57	159 ^{c}
P60	267	20	45 ^{b}	693	68	97 ^{c}

On the other hand, compared with the control, all PAM rates reduced cumulative soil loss ranging from 12–59%, 35–78%, and 41–90% for P20, P40, and P60 rates, respectively during Storms 1 to 6 (Figure 4b). For all the PAM rates, the maximum percentage reduction in soil loss was observed during the first and minimum was observed during the last storm. After six storms, the total soil loss decreased in the order C > P20 > P40 > P60 (Table 2). Despite the fact that all PAM rates reduced both runoff and soil loss, P40 and P60 reduced median cumulative soil loss significantly, compared with the control, however, there was no significant difference in the reduction caused by P40 and P60 treatments. (Table 2).

3.4. Effect of PAM, Gypsum, and Lime on Infiltration Rate (IR), Runoff, and Soil Loss

As P40 was determined as the effective rate in the first phase of the experiment, it was applied mixed with gypsum or lime at the same rate and subjected to the same number of storms as PAM treatments. During Storm 1, the highest IR was observed for gypsum treatment (41 mm h^{-1}) i.e., an increase of 21% compared with the control while the lowest was observed for P40 (26 mm h^{-1}) with reduction of 24%. During Storms 2 to 6, as the rain progressed, IR continued to decrease for all the treatments, except P40 in the order P+L > P+G > G or L > C (Figure 5). However, IR for P40 treatment sharply increased during Storm 3 and reached its maximum (28 mm h^{-1}, 268% increment) during Storm 4, however, it continuously dropped during Storms 5 and 6. Thus, for Storms 4 to 6, IR decreased in the order P40 > P+L > P+G > G or L > C, with respective final IR increment of 182%, 100%, 63%, 9%, and 4% (Figure 5). Due to the reduced IR during Storm 1, runoff from P40 increased by 28% during Storm 1 but decreased up to 33% in the subsequent storms. For other treatments, reduction in cumulative runoff ranged between 8–37% for P+L, 7–28% for P+G, 1–24% for gypsum, and 0−11% for lime (Figure 6a).

On the other hand, the amount of cumulative soil loss consistently increased in the consecutive storms in the order of P40 < P+L < P+G < G < L < C, with percentage reduction ranging between 35–78% for P40, 20–56% for P+L, 11–48% for P+G, 8–44% for gypsum, and 2–26% for lime, compared with the control (Figure 6b). At the end of six consecutive rainfall storms, both total runoff and soil loss increased in the order P40 < P+L < P+G < G < L < C (Table 3). The statistical analysis using Kruskal-Wallis test (at $\alpha = 0.05$) revealed that P40 and P+L treatments reduced median cumulative runoff and soil loss significantly, however, there was no significant difference in reduction between them while the runoff and soil loss from both gypsum and lime were not statistically different with that of the control (Table 3).

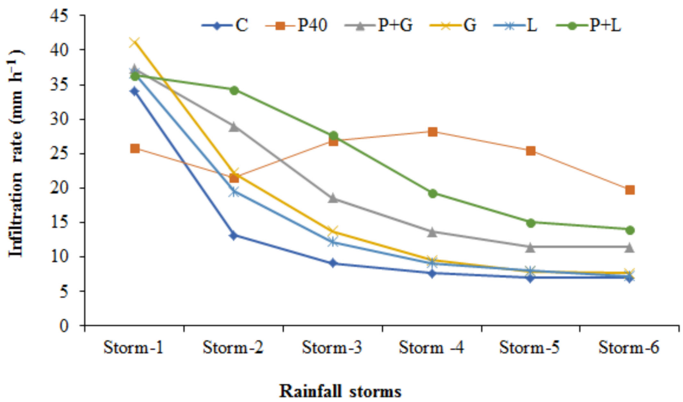

Figure 5. Effect of treatments on infiltration rate (mm h^{-1}). Each of the six storms had an average rainfall intensity of 70 mm h^{-1} for 1 h duration and 48 h drying period interval. Treatments were control (C), 40 kg ha^{-1} (P40), PAM of 40 kg ha^{-1} + Gypsum (4t ha^{-1}) (P+G), Gypsum (4t ha^{-1}) (G), lime (2t ha^{-1}) (L), and PAM of 40 kg ha^{-1} + Lime (2t ha^{-1}) (P+L).

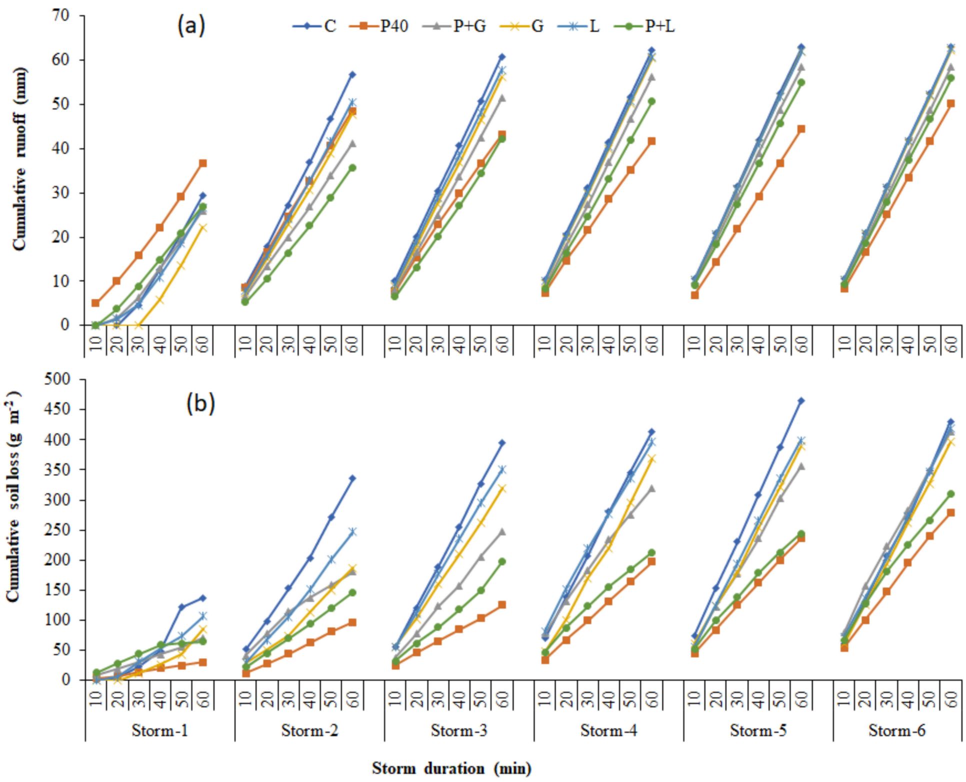

Figure 6. Effect of treatments on (**a**) cumulative runoff (mm) and (**b**) cumulative soil loss (g m^{-2}). Each of the six storms had an average rainfall intensity of 70 mm h^{-1} for 1 h duration and 48 h drying period interval. Treatments were control (C), 40 kg ha^{-1} (P40), PAM of 40 kg ha^{-1} + Gypsum (4t ha^{-1}) (P+G), Gypsum (4t ha^{-1}) (G), lime (2t ha^{-1}) (L), and PAM of 40 kg ha^{-1} + Lime (2t ha^{-1}) (P+L).

Table 3. Effect of treatments on total runoff and total soil loss with respective percent reduction (%) compared with the control and storm cumulative median runoff and soil loss from the six storms. Different letters following treatments indicate a significant difference between treatments using the Kruskal–Wallis test ($\alpha = 0.05$). Treatments were control (C), 40 kg ha^{-1} (P40), PAM of 40 kg ha^{-1} + gypsum (4t ha^{-1}) (P+G), gypsum (4t ha^{-1}) (G), lime (2t ha^{-1}) (L), and PAM of 40 kg ha^{-1} + Lime (2t ha^{-1}) (P+L).

Treatments	Runoff			Soil Loss		
	Total Runoff (mm)	Reduction in Total Runoff (%)	Cumulative Median Runoff (mm)	Total Soil Loss (g m^{-2})	Reduction in Total Soil Loss (%)	Cumulative Median Soil Loss (g m^{-2})
C	335.67		62.17 ^{a}	21.52		407 ^{a}
P40	265.04	21	44.75 ^{c}	9.19	57	159 ^{d}
P+G	291.44	13	54.88 ^{bc}	16.16	25	298 ^{bc}
G	313.33	7	58.00 ^{ab}	17.96	17	334 ^{ab}
L	322.44	4	59.92 ^{ab}	19.08	11	354 ^{ab}
P+L	266.94	20	47.42 ^{c}	11.53	46	188 ^{cd}

3.5. Effect of Aggregate and Structure Stability on Runoff and Soil Loss

Aggregate and structure stability, as described by SI, is an index that indicates the status of the soil aggregates in each treatment at the end of the experiment. After six consecutive rainfall storms, SI in P60 increased by 26% while it increased by 21% both in P40 and P+L compared with the control. The SI for all other treatments increased by less than 17% (Figure 7). In addition, both the total runoff and total soil loss showed a strong negative linear relationship with SI ($R^2 > 0.9$) (Figure 7).

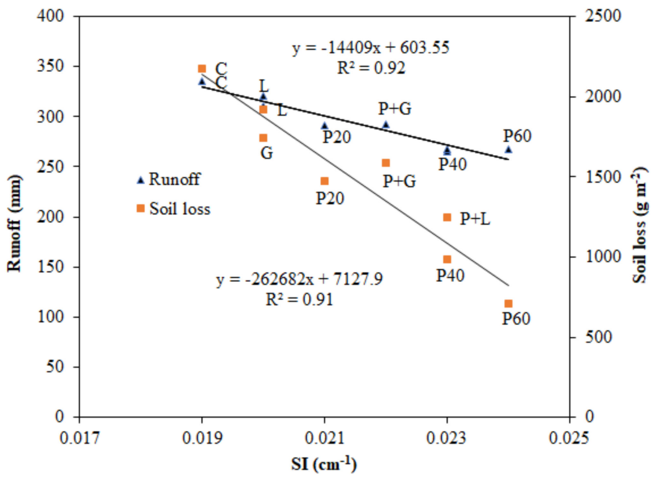

Figure 7. Relationship between structural index (SI) at the end of simulation with runoff (triangle) and soil loss (square).

4. Discussion

4.1. Effect of PAM Rates on TRO, IR, Runoff, and Soil Loss

The shorter TRO from PAM treatments, when compared with the control, was because of the high viscosity caused by the dissolution of PAM granules that led to a decrease in the IR and an increase in runoff [28,33]. Our result is consistent with the report by Lee et al. [51] who measured TRO for a silt loam soil amended with three granular PAM rates (0, 20, and 40 kg ha^{-1}), at a slope of 10%, 20%, and 40%. They found that the application of PAM (P20 and P40) decreased TRO for the 10% slope by an average of 5%.

During Storm 1, IR for all the PAM rates reduced, compared with the control (Figure 3). Nevertheless, IR from control was significantly reduced and became the lowest through Storms 2 to 6. This result is in agreement with observations by Inbar et al. [52], who used different granular PAM rates and consecutive rainstorms to mitigate post-fire soil erosion. They reported that the IR for control was higher during the first storm compared with the PAM treated setup. However, the effect of PAM treatments on IR and runoff in this study was not consistent. The application of granular PAM at higher rates (P40 and P60) decreased IR and increased runoff during Storms 1 and 2, compared with the control. However, IR for these rates substantially increased during Storms 3 and 4 while IR from lower rate (P20) decreased continuously through Storms 1 to 6. The mechanism responsible for decreasing IR and increasing runoff for the PAM treatments during the initial storm events was not the soil surface seal formation, as is the case with the control, but the large viscosity in the soil solution produced by the dissolution of PAM granules [52]. On the other hand, the reduction in IR from control during Storms 2 to 6 was due to the breakdown of aggregates by raindrop impact and subsequent seal formation [53].

On PAM dissolution during a rainfall event, the dissolved molecules are partially sorbed on the soil clay particles and improve aggregate stability, thereby increasing their resistance to detachment. Moreover, the non-sorbed segments of the molecules extend into the pores and drag the infiltrating water [40], decreasing the hydraulic conductivity of the soil and thus the infiltration rate [18]. However, the effect of viscosity disappeared after drying cycles, when the formation of bonds between PAM and soil particles was favored [39] and the positive effects of PAM applied at higher rates were enhanced after two raining and drying cycles that reversed the situation and sharply increased IR and decreased runoff later during Storms 3 and 4. The decrease in viscosity of the percolating solution together with the stabilization of aggregates through wetting and drying periods [52] led to an increase in the IR and a decrease in runoff during Storms 3 and 4 [18,28,33]. The IR, however, continuously declined during Storms 5 and 6, mainly due to washing out of PAM by runoff in the consecutive storms [52].

Furthermore, there was an increased reduction in IR with an increasing PAM rate at the beginning of the simulation; however, this reduction was reduced with increasing PAM rate at the latter stage of the simulation (Figure 3). This implies that higher PAM rates could either be applied as a split application or each of the first two rainfall storms could be applied in two or more applications with fair drying period intervals to minimize the excess runoff at the beginning.

Despite the higher runoff volume during Storms 1 and 2 as a result of high viscosity, higher PAM rates were effective in reducing soil loss throughout the consecutive storms. Similarly, Abrol et al. [40] reported that soil erosion decreases with an increase in viscosity of runoff in spite of the increase in runoff volume. Likewise, Inbar et al. [52] observed that increased viscosity of runoff reduces flow velocity and shear or drag forces that can detach soil particles. Furthermore, unlike the cumulative runoff and IR, cumulative soil losses for PAM treatments consistently decreased with increasing PAM rate but increased with time during the consecutive storm events. The reduction in soil loss with increasing PAM rate in this study is consistent with the results of Lado et al. [39], who reported that the relative viscosity of runoff increases with increasing granular PAM rate, thus decreasing runoff erosivity and hence soil loss. The consistent reduction in soil loss with increasing rates of PAM could also be attributed to the increased positive effect of PAM in preserving the soil aggregate structure [35] by increasing the soil erodibility resistance even during the last storm, which is in accordance with the reports by other researchers [27,54].

Similarly, the increase in soil loss for all PAM rates in the subsequent storms can be explained by the loss of effectiveness of PAM with time (e.g. dissolution, washing, and leaching), causing a decrease in IR and an increase in runoff, thus leading to increased soil loss during the last storms. The results from our study agree with the results of [55], who reported that the cumulative soil loss increases with increasing rainfall duration for each granular PAM rate because PAM effectiveness diminishes with time [39,51]. Furthermore, the lower PAM rate loses its effectiveness faster towards the end of the simulation when compared with the higher rates which could be due to the washout of PAM by runoff in the consecutive storms [52,54]. This leads to increased detachment and wash-in of the finer clay particles that plug the soil pores more at lower PAM rate (P20) because of the unavailability of sufficient PAM to protect the soil [25].

At the end of the simulation, it was observed that all the PAM rates were more effective at reducing total soil loss than total runoff, due to increased runoff observed at the beginning. This is in agreement with the observation made in a study by [18], who reported that the granular PAM application has less influence on runoff than soil loss. Furthermore, P40 and P60 reduced the median cumulative runoff and soil loss significantly, compared with the control, however, there was no significant difference in reduction when compared with each other, implying that P40 was the most suitable application rate (cost-effective) in reducing both runoff and soil loss from the given test soil under consecutive storms (Table 2). Nevertheless, higher final IR (Figure 3) and increased aggregate stability (Figure 3) after the last storm indicated that the PAM rates, especially the higher rates (P40 and P60) were still effective to reduce runoff and erosion for some more storms. The following figure (Figure 8) shows crusting of soil surfaces after six consecutive storms.

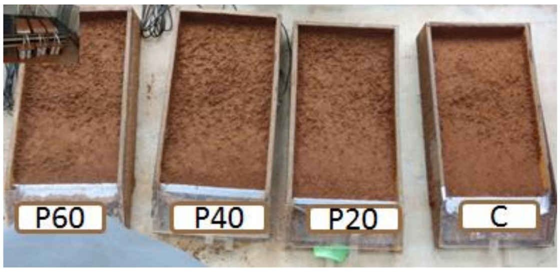

Figure 8. Crusts formed on the soil surface after six consecutive storms. Treatments were control (C), PAM of 20 kg ha^{-1} (P20), 40 kg ha^{-1} (P40), and 60 kg ha^{-1} (P60).

4.2. Effect of Gypsum, Lime, and Their Mixture with PAM on TRO, IR, Runoff, and Soil Loss

The reduction in TRO for PAM mixed with gypsum or lime treatments, as compared with the control, was attributed to the increased viscosity from the dissolution of PAM granules that reduced IR and increased runoff. On the other hand, the long TRO from gypsum could be related to the high solubility of gypsum that interacts with the soil faster. Our result agrees with the findings of [25], who compared the effects of phosphogypsum powder (PG) (5 t ha^{-1}) and granular PAM (20 kg ha^{-1}) on TRO, runoff, and erosion using a highly weathered Brazilian Alfisol. They reported that compared with control, the application of gypsum was effective in delaying runoff by increasing the TRO by 75%, whereas PAM and P+G decreased TRO by 16% and 85%, respectively. They attributed the longer TRO from gypsum treatment, which led to increased IR and delayed runoff, to changes in soil surface chemistry and the shorter TRO in PAM treatment to increased viscosity of the runoff.

The IR, runoff, and soil loss from gypsum, lime, and PAM mixed with gypsum or lime amendments varied during the consecutive rainfall storms. In the beginning, IR for P40 treatment was lower than that for other treatments and the control (Figure 5), due to increased soil solution viscosity, as discussed in Section 4.1. However, the effect of viscosity on the P40 solution started disappearing during Storm 3, when there was enough rainfall for the complete dissolution of the PAM and drying period for irreversible bonding or sorption to the soil aggregates [36]. This improved soil aggregate and structural stability increased IR and decreased cumulative runoff from P40 treatment substantially during Storms 4 to 6, compared with the control (Figure 5, Figure 6a). Despite the high runoff during Storms 1 and 2 from P40, cumulative soil loss from P40 was the lowest of all the treatments throughout the consecutive storms (Figure 6b), because the increased viscosity reduced the erosivity of the runoff at the beginning [52]. But when the viscosity decreased latter in the consecutive storms, PAM became adsorbed to and bound soil particles through cation bridging, thus, increasing aggregate stability and cohesion strength between the soil particles and decreasing soil erosion [56]. Thus, depending on the treatments and storm period, amendments affected surface soil aggregates and structural stability differently (e.g., resistance to disintegration and macro porosity).

Both gypsum and lime treatments increased IR, compared with the control (Figure 5). The higher IR from gypsum at the beginning could be due to the high solubility of gypsum, that it is likely to dissolve, release Ca^{2+} cations, and interact with the soil at a faster rate than lime [57]. On the other hand, the lower IR from lime implied the occurrence of higher dispersion from the lime treatment that sealed soil pores and decreased IR in the subsequent storms. As a result, runoff and soil loss from lime was higher than that from gypsum, and this difference in the two treatments could be explained by the varying effects of the two amendments on soil properties, mainly soil pH (Table 1).

Upon dissolution, lime dissociates into calcium and carbonate ions. The carbonate combines with hydrogen ions from the soil to form carbon dioxide and water. The removal of hydrogen ions from the soil in the form of water due to lime addition leads to an increase in negative charges in the soil while raising soil pH; hence the repulsive forces dominate between the soil particles and lead to dispersion [58–60] that seal soil pores and decrease IR. Our result is in agreement with the findings of de Castro and Celso [61] who studied the effect of gypsum and lime on clay dispersion and infiltration in Oxisols. They found that incorporating lime to the soil increased clay dispersion and reduced IR significantly than incorporating gypsum. Furthermore, the removal of hydrogen ions following the addition of lime to the soil in our study increased the pH of the Oxisols from 4.84 to 6.75 (Table 1). The increment in the soil pH of the Oxisols from lime addition might have also increased soil dispersion leading to a decrease in IR compared with the gypsum treatment that had no effect on the soil pH (Table 1). Similarly, Roloff [59] demonstrated the rise in pH values of oxidic soils leads to clay dispersion that seals pores in the soil surface and decreases IR. In addition, de Castro and Celso [61] have also highlighted a negative correlation between pH values and infiltration rate in acidic Oxisols, i.e., the IR was found to decrease significantly with increasing lime application rates.

In the case of P40 mixed with gypsum or lime treatments, increased cumulative runoff and cumulative soil loss was observed, compared with P40 alone treatments (Figure 6a,b). This can be explained by the increase in cations in the soil solution with the addition of gypsum or lime mixed with P40 promoted coiling of the dissolved PAM molecules and reduce the interaction of the charged functional groups with soil particles [39]. This reduces PAM effect on aggregate stabilization, increases surface seal formation, runoff and soil loss.

On the other hand, the presence of a higher concentration of electrolytes in P + G treatment, (4 t ha^{-1} of gypsum) compared with that in P + L (2 t ha^{-1} of lime), shortened the polymer chains and prevented the polymers from stretching and long-range bridging between the soil particles. This makes P + G less efficient in binding soil particles that are far apart and maintain soil aggregates, thus leading to increased soil erosion [18]. Hence, P + L was more effective than P + G in reducing both runoff and soil loss whereas both are less effective compared with P40 treatment. Furthermore, P + G and P + L increased IR and decreased cumulative runoff and cumulative soil loss, compared with treatments using gypsum or lime alone (Figure 6a,b). This implies that gypsum or lime was more effective for Oxisols when applied in mixture with PAM than when applied alone for Oxisols. Furthermore, the high clay content in the Oxisols could also be another factor that maintained the effectiveness of PAM alone treatment in the Oxisols [35].

The result of our study partially agrees with the study by Lepore et al. [37]. They reported that soil loss reduction in silt loam by P + G (58%) was lower than P + L (67%) while gypsum and lime reduced soil loss only by 18% and 30%, respectively. Our result was in agreement with that study in terms of highlighting that gypsum and lime were more effective when applied in mixture with PAM than when applied alone. Also, it showed that P + L was more effective than P + G in reducing soil loss. However, contrary to that study, our result showed that gypsum was less effective than lime when applied individually. The difference in the results between the two studies could be attributed to differences in soil properties (soil type, clay mineralogy), amendment rates applied [20,62], and their effect on aggregates and structural stability associated with treatments, rainfall duration, and wetting-drying condition in the two experiments. [18] also observed that the use of PAM mixed with gypsum increased the final infiltration rate and reduced runoff and wash erosion compared to application of gypsum alone in loamy sand and clay soils. Furthermore, [18] reported that application of 20 kg ha^{-1} PAM is the most effective in reducing soil losses for the silt loam and sandy clay soils compared with gypsum (2 t ha^{-1} and 4 t ha^{-1}) or 20 kg ha^{-1} PAM mixed with gypsum (2 t ha^{-1} and 4 t ha^{-1}), in spite of low IR and the resultant high runoff.

The SI of treatments after six consecutive storms also indicated that P60 increased SI by 26% while both P40 and P + L treatments increased SI by 21%, however, SI for other treatments remains lower than 17% (Figure 7), supporting the results of the effect of different treatments on runoff and soil loss. For all the eight treatments (control, PAM, G, L, and their combinations) there was a negative linear relationship between soil SI and soil loss or runoff with coefficient of determination ($R^2 > 0.9$) (Figure 7), showing that (i) both the runoff and soil loss were significantly affected by treatments and (ii) the relation between the SI and soil loss was affected more by the treatments than the relation between SI and runoff. Therefore, such an approach could be used for the evaluation of the effect of amendments on soil status to resist erosion under consecutive rainfall storms.

5. Conclusions

In this study, we tested the effectiveness of different PAM rates in reducing runoff and soil loss under consecutive rainfall storms and selected the effective PAM rate for fine-textured Oxisols. The application of PAM at a rate of 20 kg ha^{-1} (i.e., P20) was more effective in reducing runoff during the first two storms and higher rates (i.e., P40 and P60) were more effective towards the end of the consecutive storms. However, the effectiveness of PAM in reducing soil loss increased with increasing PAM rate but diminished with time over the entire duration of the simulation. Furthermore, the application of PAM leads to a better reduction in soil loss compared to runoff. Our results also revealed that reductions in runoff and soil loss by P40 and P60 were not statistically different. Hence, by taking into consideration the price and application cost, P40 was selected as the most appropriate application rate for the given test soil. The selected PAM rate was further tested by applying it mixed with sources of electrolytes (gypsum and lime), but the concurrent application of P40 with gypsum or lime was less effective in reducing runoff and soil loss than P40 alone treatments. However, as only one application rate of gypsum and lime was considered, the result from this study may not be conclusive and further tests using multiple rates of gypsum or lime mixed with P40 and wetting-drying experimental conditions are recommended. Furthermore, the split application of P40 and evaluation of its effectiveness in reducing runoff against its gross application may provide additional knowledge about the effective PAM application rate.

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