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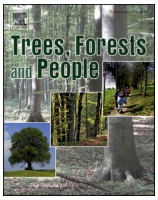

Investigating the zeolite performance in soil and water conservation after prescribed fires in degraded rangelands

Leila Gholami [a,*], Ataollah Kavian [a], Mahboobeh Kiani-Harchegani [b], Nabiyeh Karimi [a], Francisco Serrano Bernardo [c]

[a] *Department of Watershed Management, Faculty of Natural Resources, Sari Agricultural Sciences and Natural Resources University, Sari, Iran*
[b] *Ph.D. in Watershed Management Sciences & Engineering, Expert of Planning and Development Deputy, Esfahan Regional Water. Esfahan, Iran*
[c] *Department of Civil Engineering, University of Granada, 18071 Granada, Spain*

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ABSTRACT

Since the last decades, soil erosion and wildfires are significant threats to most societies and results in the loss of fertile layers and, consequently, in productivity. Changes in soil moisture and stability of soil grains, both in the short- and long-terms after a wildfire occurs, should be also considered as a parameter because they play a key role in plant growth and nutrition too. Adding conditioners to soil also helps to reduce runoff and nutrient losses, which is necessary for the sustainable use of water and ecosystem services. Therefore, the current research was conducted to assess the impacts of zeolite (microporous, crystalline aluminosilicate material commonly applied as commercial adsorbent and catalysts) conservation treatment with diverse amounts (0, 250, 500 and 750 g m^{-2}; Z0 Z1, Z2 and Z3, respectively) on changes of runoff and sediment yield in burned soils with different amounts (250, 500, 750 and 1000 g m^{-2}; F1, F2, F3 and F4, respectively) under laboratory conditions. The experiments were conducted using rainfall simulations with an intensity of 50 mm h^{-1}. The results showed that the highest changes percent of time to runoff (s), runoff volume (l), and soil loss (g) variables after zeolite application at different rates of fire was observed in F4Z3 treatment with 114.94, 76.61 and 82.60%, respectively. We conclude that these results can be useful for a better understanding of the relationships between the fire effects on runoff and sediment considering innovative application of control measures nin-tested to date.

1. Introduction

Soil is one of the most valuable natural resources utilized across socio-ecological and natural systems (Alcañiz et al., 2018), and plays acritical role in nutrient cycling, in carbon sequestration, and support for plant growth (Lehmann et al., 2020). As a result, uncontrolled degradation of the biological, chemical and physical characteristics of forest soils due to human activities can reduce their ability to better function (Ghazoul et al., 2015; Silvério et al., 2019). Especially, the fire affect many components of forest ecosystems, including vegetation, animals, soil, air, surface water, and groundwater (Lucas-Borja et a., 2021; Naserinejad et al., 2023). The fire effects can last for up to several years and the magnitude is determined by the severity of the fire (Pellegrini et al., 2021; Lucas-Borja and Zema, 2024). The wildfire can completely removes the vegetation and changes the soil characteristics and associated ecogeomorphological processes for a long time (Bento-Gonçalves et al., 2012; Estrany et al., 2019; López-Vicente et al., 2021), while the low-severity fire can change few herbaceous and shrub layers (Alcañiz et al., 2018).

Fire can alter numerous physical properties such as soil aggregates, hydrophobicity, volume density, pH, particle size distribution, color and temperature regime and some chemical characteristics (e.g. quantity and quality of organic matter, accessibility of nutrients and exchange capacity) (García-Corona et al., 2004; Agbeshie et al., 2022b; Chicco et al., 2023; Carrión-Paladines et al., 2023). Also, after a wildfire occurs, many authors highlighted an increase in soil hydrophobicity due to the reduction in permeability; however, there are several differences among regions due to the previous environmental conditions and land management (Doerr et al., 2000; Zavala et al., 2014; Agbeshie et al., 2022a; Lucas-Borja et al., 2023).

It is well-known that the fire effect on soil erosion depends on the fire intensity and, then, the rainfall characteristics after this. Understanding

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* Corresponding author.
E-mail addresses: l.gholami@sanru.ac.ir (L. Gholami), a.kavian@sanru.ac.ir (A. Kavian), mahboobeh.kiyani20@gmail.com (M. Kiani-Harchegani), nabiyeh.karimi@yahoo.com (N. Karimi), fserber@ugr.es (F.S. Bernardo).

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surface runoff after wildfires would be key to predicting the ecosystem runoff-erosion responses, anticipating risks, and implementing effective erosion mitigation actions in the post-fire (Robichaud, 2000; Robichaud et al., 2020). Interrill erosion processes after fire have been also studied in some detail at point or plot scale (0.1–2 m) using rainfall simulations (Morales et al., 2013; Poulenard et al., 2001), for example, in Europe (Neris et al., 2017) and the USA (Laflen et al., 1997, P.R. Robichaud et al., 2016). The post-fire management techniques including afforestation, seeding, mulching, salvage logging, erosion barriers or soil preparation have been developed and experimented to limit the hazardous impacts of wildfires on the forest landuses (Lucas-Borja et al., 2021).

On the other hand, researchers investigated the hydrological effects of the prescribed fire and post-fire in a large variety of environments (e.g. Albert-Belda et al., 2019; Fernández et al., 2019). In areas that have been severely burned, emergency soil stabilization treatments are frequently recommended to reduce the runoff and erosion risks after fire (Napper, 2006; Vega et al., 2014). In the world, the methods of erosion control have been extensively used for decades that those decrease the erosive energy of runoff, increase infiltration and reduce erosion (e.g. Costa et al., 2006; Fox et al., 2006; Loures et al., 2012; Kavian et al., 2018; Gholami et al., 2022).

The runoff and soil erosion can be successfully controlled by covering the soil surface, but in this field, the usage of conditioners such as zeolite can be useful in critical conditions after fire. The zeolites application has been seriously proposed by researchers as one of the most effective soil conditioners for soil and water conservation (Robichaud et al., 2010). Zeolite is a sedimentary mineral that is primarily composed of aluminum silicate and there is naturally (Pan et al., 1991). This mineral is a three-dimensional crystal lattice that can wet without changing its crystal structure (Ramesh and Damodar, 2011). Zeolite has a significant impact on improving the soil physical characteristics such as hydraulic conductivity, infiltration, and carbon sequestration. Due to its characteristics of the high porous and high suction capacity, zeolite has helped to water infiltration which helps to improving dry soils (Ghazavi, 2015). Zeolite can also absorb water up to 60 % of its weight, and as a mineral super absorbent it increases the water holding capacity (especially in sandy soil) (Gamze, 2007; Khodaei-Joghan and Asilan, 2012).

On the other hand, the usage of soil erosion plots is very important for understanding the processes of runoff and soil erosion and the effectiveness evaluation of soil erosion estimation models (Kiani-Harchegani et al., 2021). It is well-assumed that new methods are recommendable to be tested under laboratory conditions than directly on the field. They make possible to evaluate the reaction of the soil erosion process against different management options using small plots (Nearing et al., 1999). The measurement of runoff and soil erosion components in laboratory and field plots can be done using both natural rainfall or rainfall simulators. However, it should be stated that the rainfall simulator has the main advantages including the ability to control the rainfall intensity and duration and also the rainfall repeatability, that increases the data accuracy and the possibility of comparative evaluation (Cerdà, 1998; Cerda et al., 1998). One of the investigation methods of erosion and runoff yield is to transfer soil to rainfall simulation laboratories and conduct studies on prepared soil in plot scale (Iserloh et al., 2013; Mondal et al., 2021). Some studies have only focused on the fire effect on some ecosystem components (for example, vegetation, soil characteristics, runoff, and soil erosion) (Gholami et al., 2019 and 2022) but in this study, we aim to investigate the application of zeolite as a soil conditioner to reduce runoff components and sediment in post-fire conditions, creating soil erosion plots from a non-studied area located in Iran.

2. Materials and methods

2.1. Zeolite treatment

Zeolites are naturally crystalline aluminosilicates and one of the dominant minerals in sedimentary rocks. Zeolites are created in rocks of different age, lithology and geology and are a valuable indicator in sedimentary parent rocks and environmental sediments. From a structural view, zeolites are techno-silicates which represent a three-dimensional structure, including the necessary cations to balance the electrical charge of the tetrahedral units of aluminum and silicon. This conditioner, the soil properties can be improved by altering soil structure, increasing plant access to water (Mondal et al., 2021; Hazrati et al., 2022), and reducing soil particles adhesion (Xiubin and Zhandin, 2001). The used zeolite was prepared rom Semnan Mining Development Company in Iran, and its characteristics are shown in Table 1. In this study, the levels of zeolite treatments were selected with rates of 250, 500 and 750 g m^{-2}.

2.2. Soil properties

Soils from a surface layer (0–20 cm) of an eroded rangeland land was collected and transported to the laboratory for further processing (Gholami et al., 2016a; Kiani-Harchegani et al., 2021). Firstly, air-drying and removal of the pebbles and plant residues through a 4 mm sieve was conducted (Tang et al., 2006). The preliminary results on the soil of the target areas showed that organic matter, organic carbon, pH and apparent specific gravity were 0.47 %, 0.27 %, 7.86 and 0.2 g cm^{-3}, respectively. The plot surfaces were covered with artificial pumice grain (total thickness of 10 cm) for decreasing plot weight and enhancing the creation of an infiltration layer, followed by a 10 cm-thick soil layer on top each plot. After pouring the soil in the plots, the surface of the soil was rolled using a roller to achieve the apparent specific gravity of the soil in the area (e.g. Darboux et al., 2001; Defersha et al., 2011; Gholami et al., 2016b., Gholami et al., 2019).

2.3. Determining the severity levels of fire

For determining the severity levels of fire, amounts of about 250, 500, 750, and 1000 gof air-dried rangeland species residues per square meter were applied and then fire treatment was conducted in four different intensities. The application reason of the remains of rangeland plants from the native area is the possibility of generalizing and results usage for the native area. Table 2 also shows the used treatments in this study.

2.4. Plot characteristics and rainfall simulator

The used laboratory plots had the area of 0.05×0.25 m^2 and depth of 20 cm. Also, the experiments were conducted using a rainfall simulator with two Veejet 80,100 nozzles, each installed in a metal cube. The rainfall simulator was settled on metal structure of a frame with a height of 2 to 2.7 m and also the telescopic legs prepared for the appropriate establishment of simulator and suitable balance for field research. The rainfall simulator had a water pressure range of between 0 and 160 kPa (Kavian et al., 2018 and 2019) and the average terminal velocity was around 7 m s^{-1}. A digital camera (Nikon D90, 12.9 megapixel) capable of capturing 4000 frames per second was used to determine the range of raindrop sizes (Sadeghi et al., 2013). In order to enhance the precision of the measurement, we used a wooden frame (55 cm × 33 cm) with another piece of wood (3 cm × 3 cm) fixed at 0.5 m above ground level or 0.5 m below the RS (Abdollahi et al., 2021; Khaledi Darvishan et al., 2016; Kavian et al., 2019); then the photographs were taken by zooming in on the center of the frame.

Table 1
Chemical characteristics of used zeolite (%) in this study

L.O.I	NaCl	TiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	SO3	SrO	SiO2
8.3	1.3	0.3	9.5	1.8	0.5	0.6	2.7	0.4	0.1	63.1

Table 2
Used treatments of fire levels and zeolite rates in this study

Fire treatment (g)	Zeolite treatment (kg m-2)	Symbol	Replication
without Fire	0, 0.25, 0.5,0.75	CZ0, CZ1, CZ2, CZ3	3
Fire 250	0, 0.25, 0.5,0.75	F1Z0, F1Z1, F1Z2, F1Z3	3
Fire 500	0, 0.25, 0.5,0.75	F2Z0, F2Z1, F2Z2, F2Z3	3
Fire 750	0, 0.25, 0.5,0.75	F3Z0, F3Z1, F3Z2, F3Z3	3
Fire 1000	0, 0.25, 0.5,0.75	F4Z0, F4Z1, F4Z2, F4Z3	3

C: Without fire, F1: Fire with rate of 250 g, F2: Fire with rate of 500 g, F3: Fire with rate of 750 g, F4: Fire with rate of 1000 g, Z0: Without zeolite, Z1: Zeolite with rate of 0.25 kg m-2, Z2: Zeolite with rate of 0.5 kg m-2, Z3: Zeolite with rate of 0.75 kg m-2

2.5. Measurement of variables obtained during the experiments

Times were measured per intervals using a digital chronometer, then the runoff and sediment samples were collected for 10 min (Sadeghi et al., 2015; Gholami et al., 2019) for each experiment. Upon the occurrence of surface runoff, the runoff and sediment samples in plots outlet was continually collected at 2 min intervals (Kavian et al., 2018). The measurements of soil loss were conducted using a decantation procedure and oven drying at 105 °C during 24 h, and then weighed. In addition, suspended sediment concentration was computed by dividing the sediment mass by the volume of runoff collected from each sample (Ai-Ping et al., 2011; Khaledi Darvishan et al., 2015; Gholami et al., 2019). Fig. 1 shows a view of the treatments in the laboratory plots.

Finally, the ANOVA was applied to analyze treatments on the studied variables including time to runoff (s), runoff volume (l), soil erosion (g) and sediment concentration (g l^{-1}) using SPSS statistics 26 (IBM, USA). If a significant effect was found, the means were compared using Duncan's test as described in previous works of Kiani-Harchegani et al. (2021).

3. Results and discussion

3.1. Time to runoff and runoff volume

Conservation percent and ANOVA analysis of the time to runoff and runoff volume using the treated plots with zeolite (Z0, Z1, Z2 and Z3) and various fire levels (F1, F2, F3 and F4) presented in Table 3 and 4, respectively. Fig. 2 shows the effect comparison of fire and zeolite conditioner on time to runoff and runoff volume.

The results of the time to runoff from the comparison of the fire and zeolite treatments with the control treatments appeared that this variable has increased after the application of zeolite in different fire levels. The results of Table 3 showed that the conservation percentage of time to runoff at the treatment in various zeolite varied and these rates were from 1.39 to 114.94 percent. Also, the results showed that in each level of fire, with the increasing the zeolite level, the time to runoff increased.

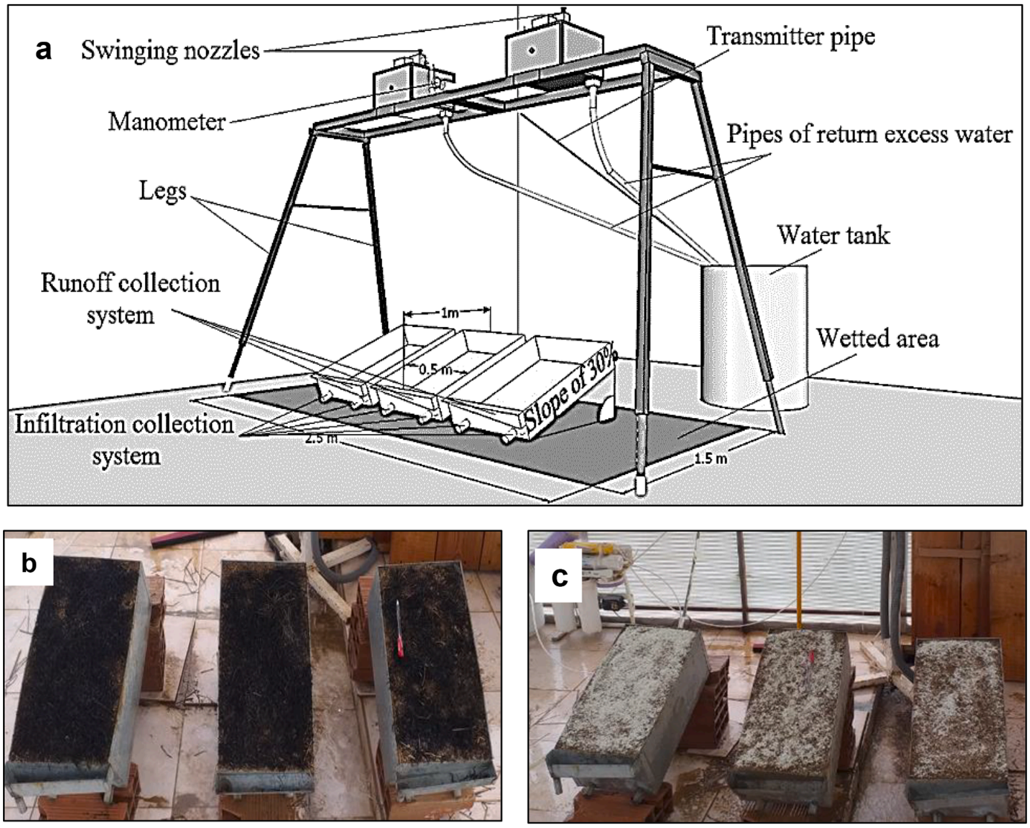

Fig. 1. Schematic of the rainfall simulator (a), A view of burned plots (b), applied zeolite on burned soil (c).

Table 3
Changes percent of time to runoff (s) and runoff volume (l) variables after zeolite application at different rates of fire

Variable	Fire treatment	Zeolite treatment				Variable	Fire treatment	Zeolite treatment			
Time to runoff		Z0	Z1	Z2	Z3	Runoff volume (1)		Z0	Z1	Z2	Z3
	C	-	12.75	17.77	14.83		C	-	11.11	31.74	38.09
	F1	-	1.61	17.30	20.04		F1	-	8.00	10.66	22.66
	F2	-	11.96	6.57	1.39		F2	-	39.84	55.46	58.59
	F3	-	73.01	43.67	46.53		F3	-	35.25	39.74	70.51
	F4	-	102.20	105.63	114.94		F4	-	60.69	72.13	76.61

C: Without fire, F1: Fire with rate of 250 g, F2: Fire with rate of 500 g, F3: Fire with rate of 750 g, F4: Fire with rate of 1000 g, Z0: Without zeolite, Z1: Zeolite with rate of 0.25 kg m-2, Z2: Zeolite with rate of 0.5 kg m-2, Z3: Zeolite with rate of 0.75 kg m-2

Table 4
The analysis of variance results in different treatments for study variables

Parameter	Variable	Sum of squares	df	Mean square	F	Sig.
Time to runoff (s)	Fire	19589.76	4	4897.44	2.13	0.095
	Zeolite	24038.31	3	812.77	3.48	0.024
	Fire × Zeolite	59719.43	12	4976.61	2.16	0.034
Runoff volume (1)	Fire	1.92	4	0.481	14.48	0.000
	Zeolite	4.86	3	1.620	48.77	0.000
	Fire × Zeolite	2.82	12	0.236	7.09	0.000
Soil loss (g)	Fire	2.94	4	0.736	0.321	0.862
	Zeolite	231.73	3	110.57	48.23	0.000
	Fire × Zeolite	149.08	12	12.42	5.41	0.000
Sediment concentration $(g1^{-1})$	Fire	332.80	4	83.20	90.66	0.000
	Zeolite	14.26	3	4.75	5.18	0.004
	Fire × Zeolite	39.19	12	3.26	3.55	0.001

It can be said that after the fire phenomenon, hydrophobic phenomenon occurs in the soil. In a hydrophobic soil, when the raindrops impact on the soil surface, at first, cannot infiltrate into the soil, of occurs depending on the hydrophobicity degree. Lucas-Borja et al. (2023) showed that fire would lead to decreasing soil infiltration, which is similar to the results of this research. As a result, hydrophobicity decreases the infiltration and increases the runoff volume (Norouzi, 2013; Belcher, 2013), but after zeolite application, due to the characteristic of moisture absorption, the hydrophobic impact decreased after fire. Branvall (2007) stated that the zeolite application registers a positive effect on infiltration rate and water and soil conservation. The results of Table 4 showed that the separation impact of fire on time to runoff was not significant, but the zeolite and the interaction effect of fire and zeolite were significant at level of 95 %. Jarosz et al. (2022) also stated that zeolite are safe for the environment and living organisms, and their multidirectional use in agriculture results primarily from their high porosity, sorption-ion-exchange capacity and well-developed specific surface area. Therefore, it can be said that the zeolite treatment and the interaction impact of zeolite and fire could increase the time to runoff because the zeolite treatment had more absorption.

When hydrophobic conditions were present, marked changes in the runoff hydrographs over time allowed for the determination a hydrophobic When hydrophobic conditions were present, marked changes in the runoff allowed for the determination a hydrophobic (Robichaud et al., 2000).

The comparison and separation of treatment levels into homogeneous groups using Duncan’s test showed that all amounts of zeolite (the condition without fire) including CZ0, CZ1, CZ2, and CZ3, had in first and second subgroups. CZ0 (conditions without fire and without zeolite) registered the elevatest amount of time to runoff generation. Z3 treatment at the F3 fire level had the highest enhancement in time to runoff generation, and Z0 treatment at the F4 fire level showed the lowest rate of time to runoff generation (Fig. 2). On the other hand, by increasing the zeolite amount, the time to runoff significantly increased in all treatments with fire and non-fire. These results confirmed that zeolite had a positive and significant effect on time to runoff in treatments of fire and non-fire. Also, Behzadfar et al. (2017) confirmed that the time to runoff increased with increasing of zeolite amount. But Girona-García et a. (2021) stated in a study all types of treatments (straw, wood-based, and hydromulch) significantly reduced post-fire soil erosion, but that only the cover and barrier treatments significantly reduced post-fire runoff. Also, the results showed that, after fire, the runoff amount increased compared to the control treatment (Table 3). Pereira et al. (2018) and Lucas-Borja et al. (2019 and 2023) confirmed the reduction effect of the vegetation cover caused by fire on increasing the runoff amount. on the other hand, Bhattacharyya et al. (1998) stated that the zeolite could increase the infiltration amount in soil between 7 and 20 %. Therefore, it can be said that, the zeolite application to the burnt soil can increase the infiltration rate and therefore decrease the runoff volume (Certini, 2005).

The results in Table 4 showed that the fire and zeolite impact and also these interaction impacts on the runoff volume were significant at level of 99 % (Robichaud, 2000). Wuest et al. (2005), Hubbert et al. (2006) and Akbarzadeh et al. (2016) stated that soil infiltration decreased under fire influence, so runoff volume increases when there is an increasing fire level and a reduction in soil infiltration. The application of zeolite amount at different levels after fire could decrease the runoff volume (Table 3). Ghazavi (2015) confirmed the positive impacts of zeolite on runoff volume and soil drainage using a rainfall simulator. Therefore, it can be said that the zeolite treatment with increasing infiltration could decrease the hydrophobic phenomenon and also the runoff volume.

Among all treatments, Z3 showed the high amount in decreasing the runoff volume without fire and Z0 obtained the highest rate of runoff volume at fire level 4 (Fig. 2). Other researchers, including Pierson et al. (2008), Inbar et al. (2014), Robichaud et al. (2016b) and Nunes et al. (2020), reported that the runoff volume increased with fire intensity. Also, Bernardi et al. (2010) reported that the zeolite increases the water holding capacity of soil. In this research, the zeolite application controlled the soil moisture content and reduced the runoff volume after fire.

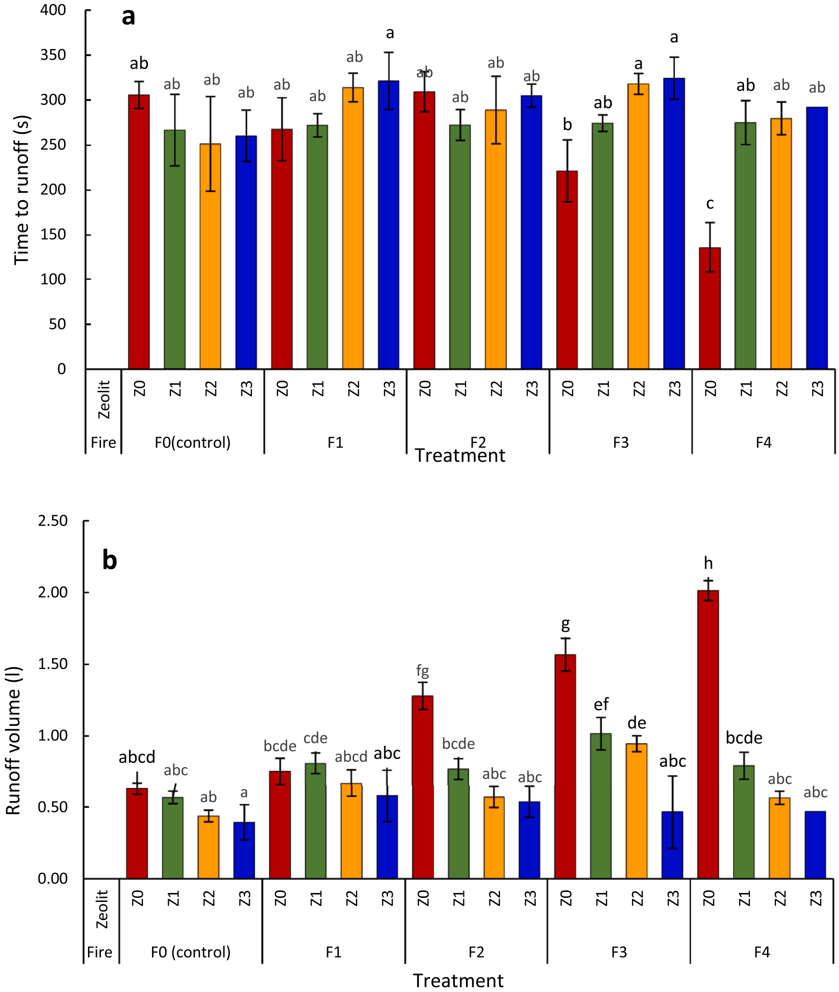

Fig. 2. Effect Comparison of fire and zeolite conditioner on time to runoff (a) and runoff volume (b)F1: Fire with rate of 250 g, F2: Fire with rate of 500 g, F3: Fire with rate of 750 g, F4: Fire with rate of 1000 g, Z0: Without zeolite, Z1: Zeolite with rate of 250 g m^{-2}, Z2: Zeolite with rate of 500 g m^{-2}, Z3: Zeolite with rate of 750 g m^{-2}.

3.2. Soil loss and sediment concentration

There were changes in percent of soil loss and sediment concentration for control and zeolite treatments (Z0, Z1, Z2 and Z3) and various fire levels (F1, F2, F3 and F4), which are representedin Table 5. Also, in Fig. 3, it is depicted the comparison among fire and zeolite impacts on soil loss and sediment concentration.

The results showed that, after fire, the soil loss reached the maximum values compared to the control treatment. The reduction of soil porosity could generate the hydrophobic layer after fire, leading to a decreasein the infiltration (Shakesby et al., 2000). Mataix-Solera et al. (2011); Inbar et al. (2014) and Garrido-Ruiz et al. (2022) also stated that the fire caused decreasing in the stability of soil aggregates and water retention. These researchers stated that the soil structure can be altered by fire and it influence on porosity and other hydrological characteristics. Also, fire increases the accumulation of hydrophobic materials on the soil surface and reduces infiltration and increases runoff and soil erosion (Keessstra et al., 2014 and Keesstra et al., 2016), as a result, the amount of sediment concentration increases. The comparison results showed that the soil loss after zeolite application at different fire levels was reduced compared to the control treatments (Table 5). Gimeno-García et al. (2007), in Mediterranean burned shrub lands showed that the soil loss had the high amount compared to the unburned soils. Noorzoi (2013) stated that, after fire, the hydrophobic soils can significantly cause the

Table 5
Changes percent at soil loss and sediment concentration after zeolite application at different rates of fire

Variable	Fire treatment	Zeolite treatment				Variable	Fire treatment	Zeolite treatment			
Soil loss (g)		Z0	Z1	Z2	Z3	Sediment concentration (g 1^{-1})		Z0	Z1	Z2	Z3
	C	-	2.17	24.78	25.54		C	-	9.34	11.53	20.05
	F1	-	14.24	32.03	38.33		F1	-	21.13	24.90	21.41
	F2	-	37.23	51.58	57.80		F2	-	1.60	5.48	0.66
	F3	-	56.23	65.60	68.69		F3	-	32.54	44.08	5.32
	F4	-	72.78	78.28	82.60		F4	-	32.28	21.84	25.96

C: Without fire, F1: Fire with rate of 250 g, F2: Fire with rate of 500 g, F3: Fire with rate of 750 g, F4: Fire with rate of 1000 g, Z0: Without zeolite, Z1: Zeolite with rate of 0.25 kg m-2, Z2: Zeolite with rate of 0.5 kg m-2, Z3: Zeolite with rate of 0.75 kg m-2

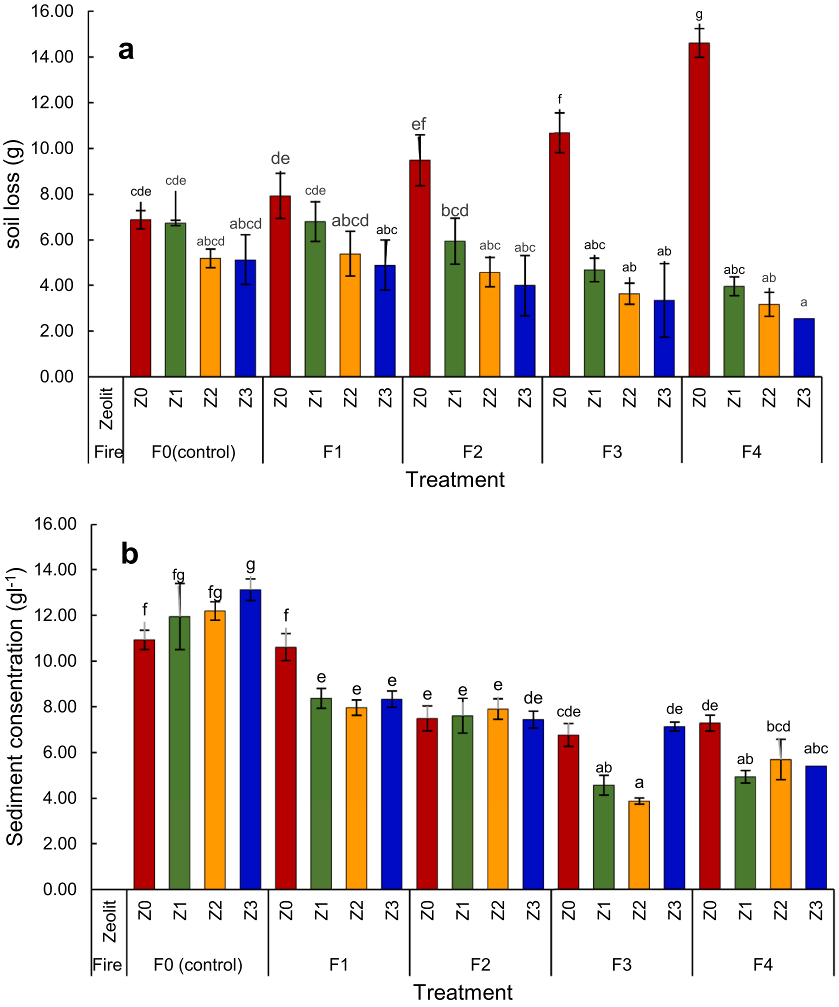

Fig. 3. Comparison of fire and zeolite impacts on soil loss (a) and sediment concentration (b)
F1: Fire with rate of 250 g, F2: Fire with rate of 500 g, F3: Fire with rate of 750 g, F4: Fire with rate of 1000 g, Z0: Without zeolite, Z1: Zeolite with rate of 250 g m^{-2}, Z2: Zeolite with rate of 500 g m^{-2}, Z3: Zeolite with rate of 750 g m^{-2}.

splash erosion and rail erosion and therefore it has the great impact on the amount of soil loss. Also, Behzadfar et al. (2017), using zeolite, showed that it had a positive impact on soil loss and was able to reduce the soil loss and sediment concentration. Recently, Lucas-Borja and Zema (2024) stated that at a comparable rainfall erosivity (difference in EI_{30} between the two sites lower than 40%), soil loss decreased by 67 (in the case of timely distribution) and 33 % (when the action is delayed) in mulched sites compared to the untreated areas.

3.3. Analysis of variance results in different treatments for study variables

The results of analysis of variance showed that the fire impact on soil loss was not significant, but the zeolite and the interaction impact of fire and zeolite were significant at the level of 99 % (Table 4). Fire causes the decreasing organic matter and stability of soil aggregates and therefore the amounts of soil erosion sharply increase after fire. The presence of higher organic matter contents (in areas with denser vegetation cover) increases the resistance of soil aggregates. Also, Weishmaier and Smith (1978) stated that the amount of soil organic matter has a high correlation with the amount of soil erodibility. The soil conditioners and also soil organic matter bind the soil particles and increase the size of soil aggregates and therefore these significantly effect on changing the soil loss (Bankoa et al., 2005; Mohabati et al., 2021). In a study at the watershed level results of De Girolamo et al. (2022) showed post-fire mitigation treatments like straw mulching and erosion barriers effectively reduced soil erosion in high- and moderate-severity fires (19.12 t $ha^{-1}yr^{-1}$ and 20.93 t ha^{-1} yr^{-1}, respectively). Therefore, after zeolite application on the burned surfaces, due to an increasing stability of soil aggregation, the amount of soil loss decreased compared to the treatments without zeolite. Fig. 3 showed that the among all treatments, Z3 and Z0 treatments at the F4 fire level had the maximum and minimum reduction in soil loss, respectively.

The results of sediment concentration after zeolite application in F1 and F4 treatments showed that this variable decreased compared to the control treatment (Table 5). According to the results, in the control treatments after fire, the reason of increasing the sediment concentration could be due to the destruction of soil aggregates. Gholami Gohra et al. (2010) coincided that a burned rangeland also registered the highest amount of runoff volume and soil sediment compared to non-burned one. Benkova et al. (2005) investigated the zeolite effect on the stability of soil aggregates and showed that the average diameter of soil aggregates increased because zeolite had the significant impact on the binding of soil particles. The results of Table 4 showed that the separation effect of fire and zeolite and these interactions on sediment concentration were significant at level of 99 %. According to Xobin and Zhandin (2001), soil with zeolite can increase soil infiltration from 7 to 20 %. Therefore, we observed that zeolite application on the burned surfaces has led to an increasing infiltration rate and decreasing runoff and sediment concentration compared to the control of burned treatments. Fig. 3 showed that among all the treatments, the Z2 treatment at

F3 fire level had the maximum reduction in amounts of sediment concentration, while the Z3 treatment at zero fire level had the maximum rate of sediment concentration. Some researchers investigated that the high fire intensity increased the sediment concentration and decreased soil infiltration (Robichard et al., 2016). The positive and significant effect of zeolite on soil drainage and infiltration confirmed by Gazavi et al. (2015). On the other hand, some studies have confirmed the positive effect of using mulches such as straw and stubble in reducing soil erosion, such as Lucas-Borja et al. (2019), who concluded that straw mulch is efficient management in recent fire-affected mountainous terrains to control soil loss immediately after wildfire.

4. Conclusion

Variable surface conditions are common in rangeland environments especially after prescribed fires. The application rainfall simulation techniques provide a reliable method to determine hydraulic conductivity for these various surface conditions. In this research, the effects of different levels of fire (F1, F2, F3 and F4) and zeolite (Z0, Z1, Z2 and Z3) on the processes of runoff and soil erosion investigated in the conditions before and after rainfall. In total, the results of this research showed that the amount of soil caused erosion by it had many changes under the influence of different levels of fire and zeolite. The results showed that with increasing in fire levels, the time to runoff decreased and the runoff volume, soil loss and sediment concentration increased. According to the results, with increasing in the zeolite amounts could significantly decreased the runoff volume, sediment concentration and increased the time to runoff variable. the Z3 treatment at F1 level and Z3 treatment at F3 level had the maximum effect on the changing time to runoff. Also, Z3 treatment in the non-fired level and Z3 in the F4 level had the maximum reduction on the runoff volume. Soil loss variable had the maximum reduction at Z3 treatment for the F4 level and also, the maximum reduction of sediment concentration observed at Z2 treatment for the F3 level. Therefore, according to the importance of the desired variables in the watershed scale, it is necessary that the water and soil resources should be protected in the fired-affected areas using zeolite application. According to the obtained results using soil conditioners at the scale of plot and even watershed, it can have positive effects on the soil variables including hydrophobic, infiltration, runoff and soil loss in fired soils. Therefore, it is suggested that the different amounts of zeolite apply in field conditions or natural conditions of watersheds that have been affected by fire.

CRediT authorship contribution statement

Leila Gholami: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ataollah Kavian:** Writing – original draft, Resources, Project administration, Methodology, Data curation, Conceptualization. **Mahboobeh Kiani-Harchegani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nabiyeh Karimi:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Francisco Serrano Bernardo:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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