



## Using nano-biodegradable hydromulch to reduce runoff and soil loss in sloping land along forest roads

Meysam Khorsandi<sup>1</sup>, Ramin Naghdi<sup>1\*</sup>, Mohammadreza Khaledian<sup>2</sup>

1. Department of Forestry, Faculty of Natural Resources, University of Guilan, Sowmehsara, Guilan, Iran

2. Department of Water Engineering, Faculty of Agricultural Sciences, University of Guilan; P.O.BOX 41635-3756, Rasht, Iran & Department of Water Engineering and Environment, Caspian Sea Basin Research Center

\* Corresponding author's Email: [rnaghdi@guilan.ac.ir](mailto:rnaghdi@guilan.ac.ir)

### ABSTRACT

Soil erosion and surface runoff are among the main challenges in sloping areas that can lead to reduced soil fertility and land degradation. Nowadays, biodegradable hydromulch has been introduced as a protective solution to reduce runoff and soil loss in sloping lands. The present study aimed to investigate and evaluate the feasibility of using biodegradable hydromulch to reduce runoff and soil loss in sloping lands under laboratory conditions. The study was designed as a factorial experiment with three main factors: soil type treatments at three levels including soils from cut and fill slopes of forest road, and the soil of the machine-operating trails, protection treatments at three levels including nano-biodegradable hydromulch (NBH) with grass vegetation, simple hydromulch without vegetation (SH), and the control, and slope treatments at two levels of 10% and 30%, with three replications for each combination. These hydromulches were based on a new natural material derived from the roots of plant. Using a Kamphorst rain simulator, rainfall was simulated on all experimental units, and the amount of runoff, sediment yield, and soil loss were measured. The analysis of variance results showed that the effect of slope on soil loss, sediment yield, and sediment concentration was significant ( $p < 0.05$ ), so that by elevating slope, soil loss and sediment yield increased significantly. Soil type did not have a significant effect on runoff and sediment yield ( $p > 0.05$ ). The results of protection treatments effect showed that the use of hydromulches, especially NBH in combination with grass, significantly reduced sediment yield, sediment concentration, and soil loss as compared to the control treatment ( $p < 0.01$ ). Compared to the control, sediment yield was reduced by 90% and 96% through the application of SH and NBH, respectively. These results indicate the high potential of SH and NBH in soil protection and erosion reduction in sloping areas. According to a simple economic evaluation, while SH is the most economical and effective option, adding grass improves protection, and the optimal choice is NBH with grass. Based on the findings of this study, the use of protective treatments, especially in lands with steep slopes, can be recommended as an effective solution in managing water and soil resources in vulnerable areas such as forest road side slopes and the machine-operating trails.

**Keywords:** Bioengineering, Erosion, Cut and fill trenches.

**Article type:** Research Article.

### INTRODUCTION

Forest road slopes and machine-operating trails are among the areas where soil is sensitive to erosion and various forms of erosion occur with the occurrence of minimal runoff flow. Without helping nature and conservation activities, it is not possible to stabilize machine-operating trails and trenches, especially embankment trenches. Nowadays, various bioengineering methods are available to protect the slopes of road trenches, but evaluation of these methods in different conditions is necessary i.e., humid or arid climates. Given the importance of soil in forest production and the long-term process of its formation, the use of bioengineering methods in erosion-

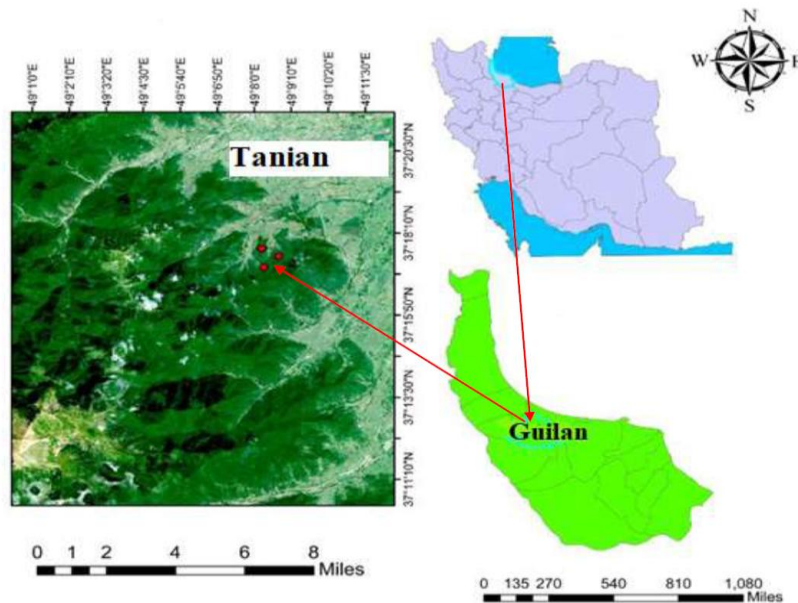
sensitive areas such as forest road trenches and machine-operating trails is necessary even at limited levels (Kavian Behjou *et al.* 2024). Using hydromulch can be considered as a proper bioengineering method to protect erosion-sensitive areas. Parhizkar *et al.* (2021) reported that hydromulch is a suitable method for erosion control, but few studies have been conducted to evaluate the effectiveness of hydromulch in erosion control in deforested areas. One of the new bioengineering methods is the employment of hydromulch, which is a new bioengineering method used to protect soil and improve plant growth conditions in natural resource systems. This material is a combination of natural fibers, polymeric materials, nutrients, and sometimes other compounds such as fertilizers, which are applied to the soil surface in a water-soluble form, sometimes with plant seeds. Hydromulch is mainly used in agriculture, irrigation, and restoration of damaged lands (Kavian Behjou *et al.* 2024; Parhizkar *et al.* 2024). Using this method can have significant effects on soil protection (Kader *et al.* 2019). Hydromulch may contain nutrients that are added to the soil and enhance the physical and chemical properties of the soil. These materials can include nitrogen, phosphorus, potassium, and other essential elements for plant growth (Parsakhoo & Hosseini 2023a). In this way, the soil is naturally fortified and provides better conditions for plant growth (Scherrer *et al.* 2020). The advantages of this method include reduced labor costs, increased work speed, and a positive impact on vegetative and protective performance of vegetation (Sprague & Prellwitz 2020). Various studies have also shown that using hydromulch requires less time to achieve vegetation cover and reduce erosion compared to traditional methods, and is also more economically viable (Faucette *et al.* 2004; Fan *et al.* 2023). Grass is usually used in the composition of hydromulches. Grass plants play an important role in preventing soil erosion due to their extensive and dense roots. This plant can prevent soil erosion and protect the soil from destructive factors such as wind and water, especially in areas with high slopes or areas with heavy rainfall (Dunkerley 2014). Grasses reduce the speed of runoff by forming a surface cover, especially in sloping areas. This helps prevent soil erosion by rain or running water (Dunkerley 2014). Grass roots increase soil permeability and help reduce runoff, which can in turn reduce erosion (Lal 2001). Straw and stubble are another material used in the manufacture of hydromulch. Roots from seeds in hydromulch bind soil particles, reducing soil detachment by runoff, similar to intact grassland cover. This process is especially important in reducing soil erosion and protecting it against heavy rainfall (Li *et al.* 2022). Sadeghi *et al.* (2014) studied the effect of rice straw and stubble on surface runoff production and soil loss in small plots. The results showed that the effect of treatments at two rainfall intensities of 50 and 90 mm h<sup>-1</sup> on reducing runoff volume was about 90 and 96%, respectively, compared to the bare soil, and the amount of soil loss was completely stopped at both intensities. Fakhari *et al.* (2018) studied the effect of rice straw, rice stubble, and wood chips on soil erosion control and seedling growth on forest road embankment slopes. In their research, the effectiveness of two types of natural mulches, wood chips, and rice straw, on the amount of runoff, sediment, and establishment of planted alder and willow seedlings on the forest road embankment slopes was evaluated in comparison with the control treatment. The results of the study showed that natural geotextiles (the effect of rice straw, rice stubble, and wood chips) exhibited a significant effect ( $p < 0.05$ ) in reducing runoff (over 90% compared to the control treatment) and sediment yield (it was completely controlled). Solgi *et al.* (2021) studied and evaluated the effectiveness of mulching to reduce soil erosion on slopes along forest roads in Hyrcanian forests. The results showed that mulch cover treatments significantly reduced the average volume of surface runoff and sediment yield compared to the bare soil. Abbasi *et al.* (2015) reported that hydromulch controlled runoff and sediment yield under laboratory conditions. Iserloh *et al.* (2015) presented the results of over 500 rainfall simulations with a small rain simulator in different regions in West and North Africa and in Southern and Central Europe. The objectives of this study were to investigate the erodibility of soil with respect to different soil cover, land use, and texture. The results showed that with a rainfall intensity of 40 mm h<sup>-1</sup> for 30 minutes, the runoff coefficient, i.e., a dimensionless coefficient relating the amount of runoff to the amount of precipitation received, changed between 0% and 100% and the amount of erosion changed between 0 and 500 g m<sup>-2</sup>. Recent studies show that the physical and chemical properties of soils, along with the slope of the area, have a significant effect on sediment yield and runoff (Solgi *et al.* 2021; Parsakhoo & Hosseini 2023a, b). In this regard, the use of rain simulators to simulate rainfall and evaluate its effects on hydrological processes is a very useful tool. These devices allow for a more detailed study of soil behavior under different precipitation conditions and can help optimize soil and water resource management (Zhao *et al.* 2023). According to the previous researches, employing mulch coatings, especially biodegradable hydromulches, has been considered as an effective method for reducing runoff and soil loss on sloping lands in recent years. Several studies, including those by Sadeghi *et al.* (2014) and Fakhari *et al.* (2018), have shown that mulches can significantly reduce the volume

of runoff and the rate of soil loss. However, many of these studies have compared types of natural or artificial mulches, but limited research has evaluated biodegradable hydromulches and their application in the specific conditions of steep slopes and forest roads. Also, recent studies indicate the need for innovative applications such as using plant and biological hydromulches to stabilize soil in vulnerable areas. Unfortunately, few studies evaluated hydromulch, nanohydromulch, and nano-biodegradable hydromulch (NBH) performance in reducing runoff and sediment yield in deforested areas. Hydromulch is a slurry mixture sprayed onto disturbed soil. It forms a protective, moist blanket that prevents seed and soil washout, promotes germination, and retains moisture until grass establish. Nanohydromulch is an advanced form of hydromulch where the nano materials are mixed in hydromulch. These materials are orders of magnitude smaller and finer than traditional materials. Nanohydromulch is more effective than hydromulch. NBH takes the nanohydromulch technology a step further by specifically engineering the nano materials from biodegradable and often renewable materials. Common sources include starch-based polymers (e.g., from corn), cellulose, or other plant-derived materials. The present study was conducted on a laboratory scale with the aim of investigating and assessing the feasibility of using NBH to reduce runoff and soil loss on sloping land along forest roads. The results of this study can be used especially in the design and implementation of protection solutions on slopes along forest roads and can also be considered as a scientific basis for sustainable management of natural resources in vulnerable areas. By introducing new hydromulches and examining their effects, this study provides a new look at traditional methods of soil erosion management and can pave the way for the development of effective and economical solutions for preserving soil and water resources in the humid climate conditions of Guilan province, Iran. The new material used in the present study is derived from the root of a plant, i.e., *eremurus* and, in addition to its proper performance, is environmentally friendly and cost-effective, that is why this material was used. Despite the demonstrated benefits of natural mulches and hydromulches in reducing erosion, few studies have quantitatively evaluated their effectiveness on forest road embankment and machine-operating trail slopes. This study addresses this knowledge gap under controlled laboratory conditions. The hypothesis of the present study was that the NBH treatment reduces runoff and soil loss better than other treatments. So that, the objective of this study was to evaluate two natural combinations of NBH and SH in reducing runoff and soil loss.

## **MATERIALS AND METHODS**

### **Study area**

The present study is a laboratory scale study using soil collected from road trenches and machine-operating trails in Parcel 6 of Series 2 of Tanian Forest located in Sowmehsara County, Guilan Province, Northern Iran. This village is located in a foothill and forested area and is located at geographical coordinates 37.2667° N and 49.1333° E and is at an altitude of 1430 m (Fig. 1). Its distance from the center of Sowmehsara County is about 10 km and accessible via local roads. Tanian Village is located in a region with a humid and temperate climate that is influenced by the humidity of the Caspian Sea and the Alborz Mountains. According to the reports of the Meteorological Organization of Guilan Province, this region has abundant rainfall, which is mostly observed in the autumn and winter seasons, with an average annual rainfall about 972 mm (Iran Meteorological Organization 2021). The temperature in summers is between 20 and 25 °C and in winters drops below zero. These characteristics cause Tanian Village to have forested vegetation. The soil of the region is mainly alluvial and loamy soils, which are fertile due to the high rainfall and forest vegetation. Trees such as oak, alder, ash, and maple grow in this region, which are natural characteristics of Hyrcanian forests. The soil of this region is capable of maintaining high humidity and is suitable for agriculture and gardening. Due to the climatic and soil conditions, the ecosystem of Tanian region includes Hyrcanian forests and small rivers and streams which feed the groundwater resource and help the growth of vegetation. This region is also a suitable habitat for a variety of native animals such as birds, wild animals, and insects. This region was selected to study the effect of hydromulches on runoff and soil loss due to its specific environmental characteristics described above, e.g. steep slopes, high rainfall, and erosion-prone soils. This laboratory scale research was conducted in the pressurized irrigation laboratory of the University of Guilan. Controlled laboratory conditions in this research is a way to isolate treatment effects and ensure reproducibility versus field conditions. The study area has specific topographic features, which mainly include different slopes. The soil of this area is a mixture of forest soils, which include specific characteristics such as organic and mineral composition, soil texture, and soil structure. These characteristics are very important for evaluating the effect of different hydromulch treatments on runoff and soil loss.



**Fig. 1.** Location of the study area on the map of Iran, Guilan Province, and location of soil sampling points.

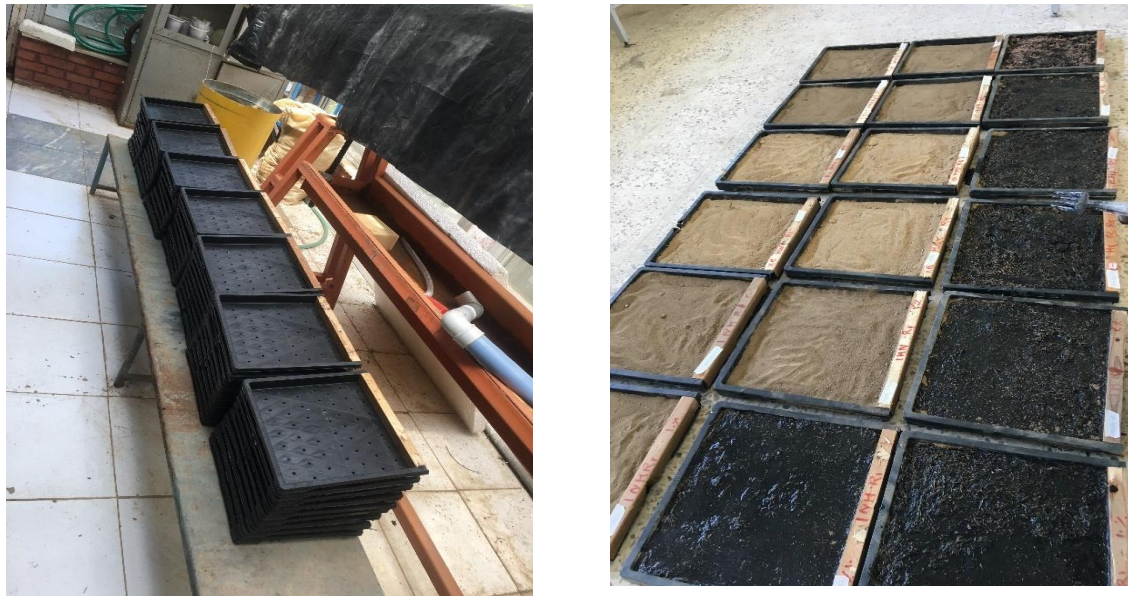
### Sampling design and field sampling

In this study, three types of forest soils from different areas were used, including the soils of the cut and fill slopes, and the soil of the machine-operating trails. These samples were taken from a depth of 0 to 30 cm of soil and were transferred to the laboratory for testing and conducting this research. Random sampling was carefully carried out for each soil sampling points and in each land use, i.e., the machine-operating trails and cut/fill slopes of forest roads, three composite samples, each obtained by mixing the three taken samples, were taken to obtain a representative sample of the intended land use for more accurate evaluation and testing. Also, soil samples were randomly collected for two slope classes (10% and 30%), resulting in 18 planting trays per soil type for experiments. In this study, two slope classes were considered: slope zero to 20, of which 10 was the average, and slope 20 to 40, of which 30 was the average and representative. These slopes were selected to simulate the natural conditions of forest lands in Northern Iran and to investigate the effects of different treatments on runoff and soil loss under different slope conditions. Different slopes were considered to evaluate the effect of slope on the severity of erosion and runoff. The collected soils were placed in the laboratory to air dry. These samples were carefully pounded and, after passing through a 2-mm sieve, were prepared for the experiments. After drying the samples in the open air and passing through a 2-mm sieve, the samples were placed in an oven at 105 °C for 24 hours to dry completely. Then, physical parameters were measured including soil texture, apparent bulk density (Singh 2024) and particle density using the pycnometer method (Singh, 2024), as well as chemical parameters including electrical conductivity (EC), pH in saturated extract (Page *et al.* 1982) and organic matter using the Walkley and Black method (Walkley & Black 1934). The study was conducted as a factorial experiment with three replications to ensure the necessary statistical accuracy of results. All three soil types were placed in three treatments: NBH with grass vegetation, SH without vegetation, and control treatment at two slopes of 10 and 30% in 25 × 25 cm-planting trays (Fig. 2). So that, there were 54 trays, i.e., soil types (3) × slopes (2) × protection treatments (3) × replications (3) = total trays (54). Replications were independent trays and were randomized.

### Preparing the treatments in the laboratory

In this study, three different treatments were investigated: Treatment 1: nano-biodegradable hydromulch (NBH) including water, grass seed, silica nanoparticles, rice husk, starter fertilizer, biochar, eremurus and sawdust; Treatment 2: simple hydromulch without vegetation (SH) including water, rice husk, biochar, eremurus and sawdust; and Treatment 3: Control (untreated soil). These treatments were considered to evaluate the different effects of the substrate on runoff and sediment production. In this study, two types of NBH and SH were selected to investigate their effects on reducing soil erosion and runoff production. Nanosilica is composed of silicon and oxygen (SiO<sub>2</sub>) and usually exists in crystalline or amorphous form. These particles have a high level of activity and can be easily combined with other materials. Nanosilica has a very high surface area, which increases their reactivity and adsorption. These are very nano silica particles, usually ranging in size from 1 to 100 nanometers.

These particles have wide applications in various industries due to their special properties. Some more specifications of the rainfall simulator are as: supplier: Sigma Aldrich, bulk density:  $2.2 \text{ g cm}^{-3}$ , and molecular weight: 60.08.



**Fig. 2.** Seedling trays used in this study (left: trays without soil and right: trays filled with soil).

In the seedling trays, after calculating the apparent bulk density of all three soils, which was about  $1.2 \text{ g cm}^{-3}$ , and considering the internal dimensions of each tray and measuring the volume of the tray, the soil weight for each tray was estimated to be about one kilogram, then one kilogram of soil from each sample (the machine-operating trails and cut/fill slopes of forest roads) was poured. It should be noted that in both NBH and SH treatments, 5% rotted manure (50 g) was mixed with soil. To prepare NBH, various materials were used, i.e., eremurus (*Eremurus himalaicus*; 1.5%), silica nanoparticles (each sample containing 1.5 g), rice husk (2%), biochar from olive kernels (1.5%), sawdust (1.5%), and starter fertilizer (with a ratio of 3 to 1 NPK fertilizer to humic acid, 5%). All quantities were measured carefully and finally these materials were mixed in a graded cylinder for each sample, then prepared by adding 400 mL distilled water to it to make a uniform mixture. After mixing, the above mixture was evenly sprinkled on the soil bed on each seedling tray in the NBH treatments (Fig. 3). Furthermore, 10 g of grass seed was spread uniformly on each seedling tray, then a fork was used to mix it with the substrate and evenly distribute the seeds (Fig. 4).



**Fig. 3.** Preparation of NBH treatment (from left to right: rice husk, biochar, sawdust, and grass seed, respectively).



**Fig. 4.** Mixing grass seed with soil (left) and leveling it (right).

To prepare simple hydromulch without vegetation (SH), a mixture of rice husk (2%), biochar (1.5%), and eremurus (1.5%), employing for the NBH treatment, was used in the same proportion and amount for each sample. These materials were also measured accurately and after adding 400 mL water, mixed and homogenized using a hand mixer. The resulting mixture was sprayed on the soil. The different materials for both hydromulch mixtures (NBH and SH) were mixed using a hand mixer after measuring. These mixtures should be sprayed evenly and carefully across the soil surface. The seedling trays were prepared accurately and after spraying the hydromulch mixture, grass seeds were sown in them. The hydromulch mixture was sprayed evenly on the soil bed to ensure better growth of grass seeds and optimal effect on the soil. *Zoysia* grass, *Zoysia japonica*, a warm-season grass with a deep root system, was selected for this study. It was planted in seedling trays under NBH treatments on August 21, 2024 in the pressurized irrigation laboratory, University of Guilan. After providing favorable conditions (water and temperature), germination began on September 10 (Fig. 5). Irrigation was performed daily using a small hand-held sprinkler. This step is necessary to provide vegetation cover on the soil surface.

#### **Measuring runoff and sediment**

Nowadays, using small and portable rain simulators has become common for comparative research in field conditions. Sadeghi *et al.* (2014) used the rain simulator of the Soil Conservation and Watershed Management Research Institute with a plot size of 0.0625 m<sup>2</sup> (25 cm × 25 cm), which was designed based on the standard model available at Wageningen University in the Netherlands, to conduct his study. This rain simulator is suitable for determining soil erosion characteristics, water infiltration rates, and soil conservation research, and its use is considered a standard method for determining the erodibility of soil surface. This simulator consists of three parts: a sprinkler with a pressure regulator to produce standard rainfall, special stands to hold the sprinkler, and a 25 cm × 25 cm plot on which the soil under study is placed. The disadvantages of this rain simulator include the lack of proper installation on steep slopes and low accuracy in correctly estimating the amount of sediment and runoff due to the small size of the study area. Also, due to its low height, this rain simulator is suitable for the relative evaluation of the effect of vegetation on the cut and fill slopes along forest road in reducing sediment yield and runoff. Some more specifications of the rainfall simulator are as: average fall height of drops = 400 mm, diameter of drops = 5.9 mm, mass of drops = 0.106 g, number of capillary tubes = 49, kinematic energy of shower = 35.4 J mm<sup>-1</sup>, and surface area of test plot = 0.0625 m<sup>2</sup> (Kamphorst 1987). The advantages of this device include low water requirements and easy portability. This device was used in the laboratory to determine the amount of sediment and runoff after leveling (Fig. 5). After the grass seed germination and proper growth stage, all samples were placed under the Kamphorst rain simulator in the laboratory on November 14, 2024 with a rainfall intensity of 3.57 mm min<sup>-1</sup>, which is similar to heavy rainfalls in the forest areas of Northern Iran (Fig. 5). To collect runoff and sediment into a collection container, a hand-crafted stainless-steel V-shaped gutter was attached to the lower edge of the trays to direct runoff and sediment into the collection container. The total runoff volume and sediment weight collected after each rainfall test from each tray were measured and weighed as described in Markou *et al.* (2007) and Silva *et al.* (2023). The samples were then placed in metal containers and dried in an oven at 105 °C

for 24 hours to determine the amounts of runoff and the weight of sediment. Total soil loss was also determined using the on-site placement method as described by Saeidi & Sadeghi (2010) and Abbas *et al.* (2021). To calculate the runoff coefficient, the total runoff volume generated during the test was divided by the total precipitation volume received by the tray.



**Fig. 5.** Preparing the rain simulator and recording the necessary data for each sample.

### **The cost of soil protection methods implementation**

In this study, a simple economic evaluation was conducted to compare the novel NBH and SH methods. Cost-benefit analysis is acceptable considering all direct initial investment costs. Cost data was collected through field implementation in a pilot experiment as well as extrapolation to arguments from reliable sources. NBH and SH costs include the price of NBH raw materials, transportation, and spraying in 2025. This analysis is designed to provide a quantitative perspective for decision-making in soil conservation projects in forested areas with limited budgets.

### **Statistical analysis**

The study was designed as a factorial experiment with three main factors: soil type treatments including soils from cut and fill slopes of forest road, and the soil of the machine-operating trails, protection treatments at three levels including NBH with grass vegetation, SH without vegetation, and the control, then slope treatments at two levels of 10% and 30%, with three replications for each combination. Laboratory data were analysed using SPSS software. Analysis of variance (ANOVA) was performed, and if significant differences were identified, mean comparisons were conducted using Tukey's method.

### **RESULTS AND DISCUSSION**

Analysis of variance of protection treatments on the three soil types including the cut and fill slopes, and machine-operating trails studied at two slopes of 10% and 30% are presented in Table 1. Slopes significantly affected sediment yield ( $p < 0.05$ ), sediment concentration ( $p < 0.05$ ), and soil loss ( $p < 0.01$ ), however did not significantly influence runoff and runoff coefficient ( $p > 0.05$ ). The effects of soil types including three soils taken from the cut and fill slopes of forest road, and the machine-operating trails on runoff, sediment yield, sediment concentration, runoff coefficient, and soil loss were not significant ( $p > 0.05$ ). However, the effects of protection treatments on runoff, sediment yield, sediment concentration, runoff coefficient, and soil loss were all significant ( $p < 0.01$ ). Albeit, the interaction effects of slope and soil types, slope and protection treatments, soil types and protection treatments, and the three factors slope, soil, and protection treatments on runoff, sediment yield, sediment concentration, runoff coefficient, and soil loss were not significant ( $p > 0.05$ ).

**Table 1.** Analysis of variance of the effect of slope, soil types (soil), and protection treatments on runoff, sediment yield, sediment concentration, runoff coefficient, and soil loss.

Source of variance	df	Mean square				
		Runoff	Sediment yield	Sediment concentration	Runoff coefficient	Soil loss
Slope	1	5488 <sup>ns</sup>	0.11*	0.281*	0.002 <sup>ns</sup>	0.313**
Error a	2	1543	0.002	0.004	0.001	0.004
Soil type	2	1267 <sup>ns</sup>	0.043 <sup>ns</sup>	0.118 <sup>ns</sup>	0.0001 <sup>ns</sup>	0.12 <sup>ns</sup>
protection treatments	2	61447**	2.30**	10.35**	0.021**	10.21**
Slope × Soil	2	15858 <sup>ns</sup>	0.008 <sup>ns</sup>	0.003 <sup>ns</sup>	0.005 <sup>ns</sup>	0.003 <sup>ns</sup>
Slope × protection treatments	2	4852 <sup>ns</sup>	0.008 <sup>ns</sup>	0.023 <sup>ns</sup>	0.002 <sup>ns</sup>	0.016 <sup>ns</sup>
Soil × protection treatments	4	17532 <sup>ns</sup>	0.04 <sup>ns</sup>	0.118 <sup>ns</sup>	0.006 <sup>ns</sup>	0.112 <sup>ns</sup>
Slope × Soil × protection treatments	4	6992 <sup>ns</sup>	0.021 <sup>ns</sup>	0.046 <sup>ns</sup>	0.002 <sup>ns</sup>	0.058 <sup>ns</sup>
Error b	32	5974	0.015	0.046	0.002	0.041

Note: ns: not significant, \*: significant at the  $\alpha = 0.05$ , and \*\*: significant at the  $\alpha = 0.01$ .

These findings are consistent with the results of many previous studies that have shown that land slope plays a decisive role in hydrological processes. In particular, elevating slope increases runoff velocity and reduces water permeability in the soil, which leads to upraised sedimentation and soil loss (Li *et al.* 2022). According to the results of the present study, the effect of soil types on various hydrological parameters was not significant. This finding may be because at the cut and fill slopes surfaces and machine-operating trails, soil structural alterations are such that their effects on hydrological characteristics are weaker compared to other environmental factors such as slope or protection treatments. These results are consistent with the study conducted by Li *et al.* (2023) in soils with different textures, which emphasize that the effects of soil types are more on the physical and chemical properties of the soil than on the hydrological parameters. The effect of protection treatments on the studied hydrological parameters was significant at the 1% probability level, indicating the effectiveness of these treatments in controlling hydrological processes and reducing soil and sediment loss. This result is consistent with studies that have investigated the effect of protection covers and management measures on reducing soil erosion. For example, the positive effect of vegetation cover and other protection methods on reducing runoff and sediment have been reported in several studies (Pimentel *et al.* 1995; Gomez & Nearing 2005). On the other hand, the interaction effects of various factors such as slope and soil types, slope and protection treatments, and other combinations on hydrological characteristics was not significant in this study. These results may be due to limitations in the experimental design or the complexities of natural processes that may alter the interactions of these factors at larger scales and under different conditions. In similar studies, the interactions between different factors in hydrological processes are complex and may change under specific environmental conditions (Zhang *et al.* 2014; Smith *et al.* 2020).

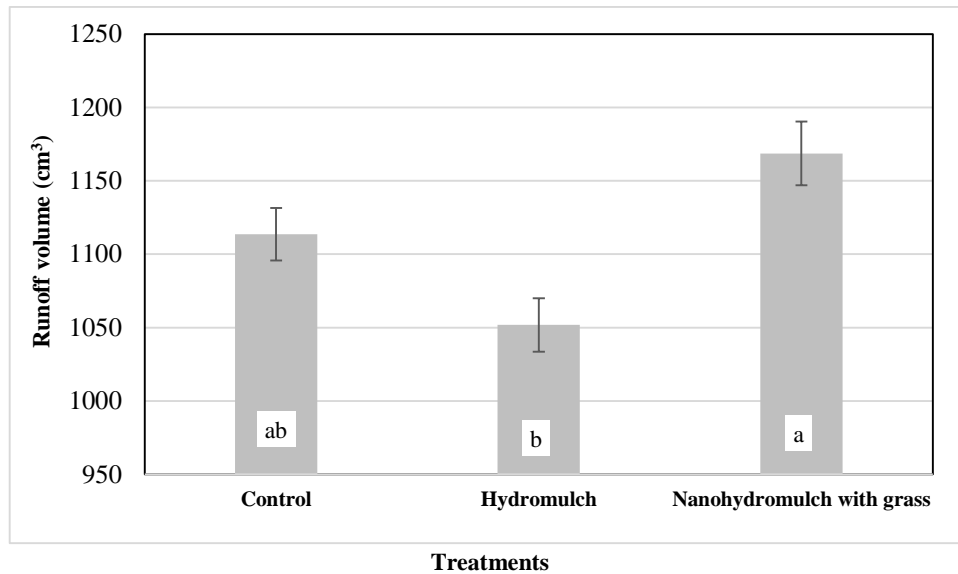
### Effects of slope, soil types, and protection treatments on runoff volume

The effect of protection treatments on runoff was significant compared to the control ( $p < 0.01$ ; Table 1; Fig. 7). The lowest runoff volume with 1052 cm<sup>3</sup> was recorded in the simple hydromulch without vegetation (SH) protection treatment compared to the other ones, especially the control treatment with 1114 cm<sup>3</sup> ( $p > 0.05$ ). This reduction may be attributed to the enhanced soil structure and increased infiltration resulting from the binding properties of SH. Previous studies have pointed out the positive effects of protective treatments on runoff reduction. For example, research has shown that using various mulches can reduce runoff volume and improve soil conditions by reducing evaporation and facilitating water infiltration into the soil (Zhang *et al.* 2020). Therefore, employing protective treatments such as hydromulch can be considered as an effective strategy in managing water resources.

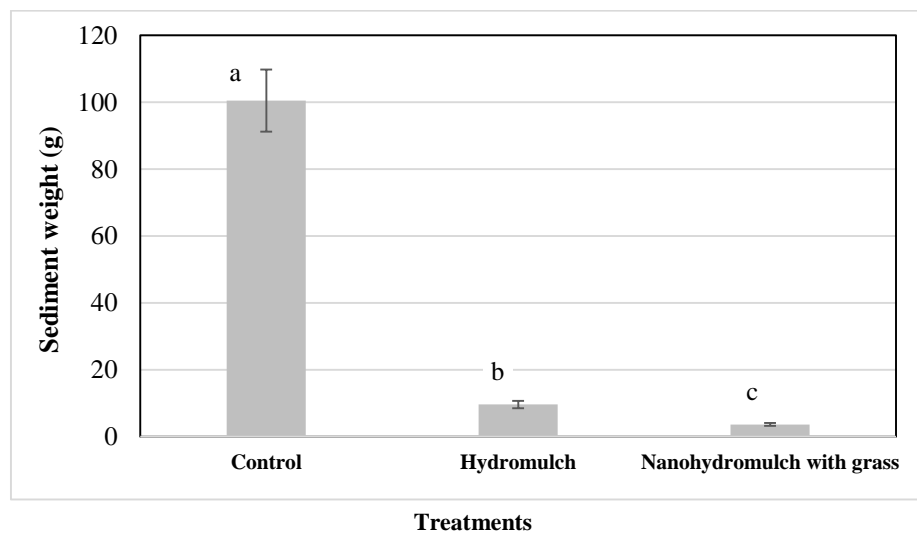
### Effects of slope and protection treatments on sediment yield

The effect of slope on sediment yield was significant ( $p < 0.05$ , Table 1). The weight of sediment produced at the 10% slope was 31.5 g, while the sediment produced at the 30% slope increased by approximately 41% to 44.4 g. The effect of protection treatments on the sediment yield was also significant ( $p < 0.01$ ; Fig. 8). The highest sediment yield was recorded in the control compared to the two other treatments ( $p < 0.01$ ). The two hydromulch treatments exhibited a significant difference and the lowest sediment yield was recorded in the NBH with grass treatment. This result indicates that by elevating slope, water flow becomes faster, which can increase the rate of soil erosion and sediment yield. Previous research has also emphasized that slope is one of the main factors

affecting the amount of sediment produced and is directly related to the intensity of soil erosion (Wischmeier 1976; Foster *et al.* 2002).



**Fig. 7.** Effect of two treatments, NBH and SH, on runoff volume compared to the control treatment, lowercase letters indicate significant differences between treatments ( $p < 0.05$ ).



**Fig. 8.** Effect of two treatments, NBH and SH, on the sediment yield compared to the control treatment.

Overall, the findings of this study indicate that the combination of slope and protection treatments can have a significant effect on erosion and sediment production management, and using nano-biodegradable hydromulch (NBH), especially in high-slope lands, can be considered as an effective strategy in controlling soil erosion and sediment yield. This reduction in sediment yield under NBH treatments is likely due to the enhanced cohesion of soil particles and improved infiltration resulting from the mulch's binding and water-retention properties.

#### **Effects of slope and protection treatments on sediment concentration**

The effect of slope on sediment concentration was significant ( $p < 0.05$ ). The sediment concentration produced at the 10% slope was  $28.8 \text{ g L}^{-1}$ , while at the 30% slope increased by 41% to  $40.5 \text{ g L}^{-1}$ . The effect of the two protection treatments on sediment concentration was also significant ( $p < 0.01$ ; Fig. 9). The highest sediment concentration was recorded in the control compared to the other treatments ( $p < 0.01$ ). The other two treatments displayed significant differences, and the NBH with grass treatment exhibited the lowest sediment concentration. Increasing the slope accelerates the flow of water and, as a result, increases the sediment carrying capacity. Various studies have also emphasized this effect. For instance, findings of Lal (2001) study on the effect of slope on soil erosion and sediment yield showed that steeper slopes usually elevate the rate of sediment yield. Zhang *et*

al. (2014) concluded in a similar study that mulches and vegetation can reduce the intensity of soil erosion on steep slopes and effectively reduce the amount of sediment concentration, thanks to the soil particles cohesion.

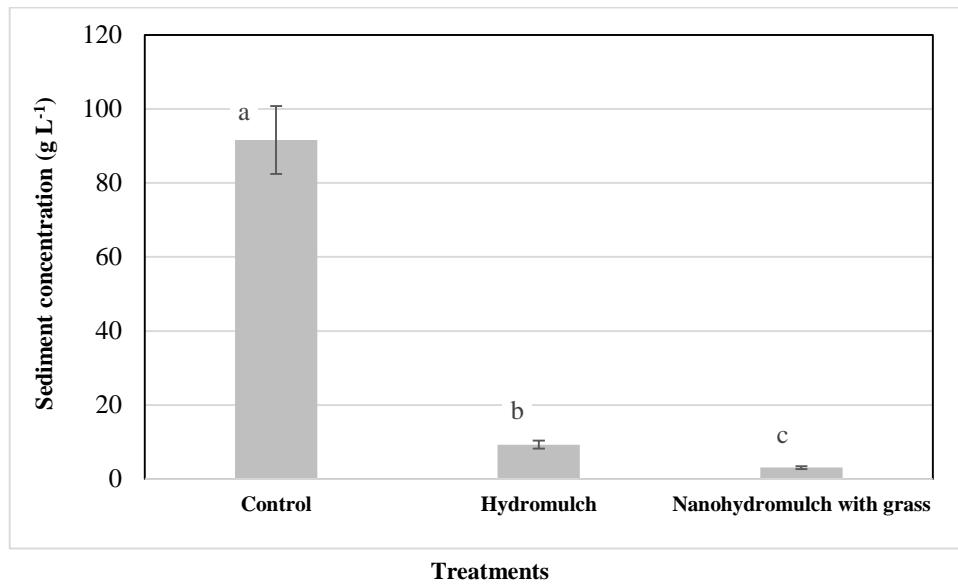


Fig. 9. Effect of two treatments, NBH and SH, on sediment concentration compared to the control treatment.

#### Effect of protection treatments on the value of runoff coefficient

The effect of the two hydromulch treatments on the runoff coefficient was significant compared to the control ( $p < 0.01$ , Fig. 10). The highest runoff coefficient (0.69) was observed in the NBH treatment with grass. Other treatments exhibited significant differences, and the lowest (0.62) was observed in the SH treatment.

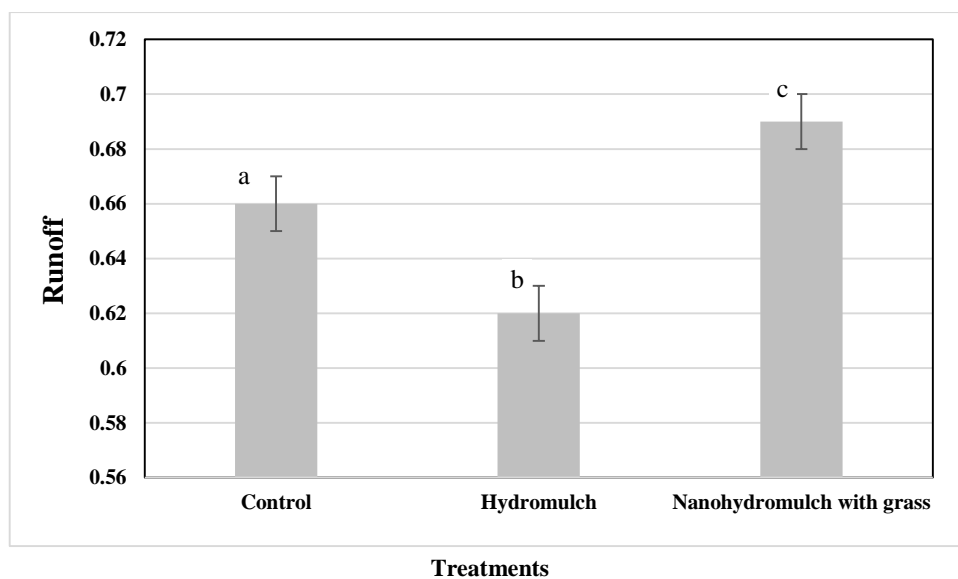
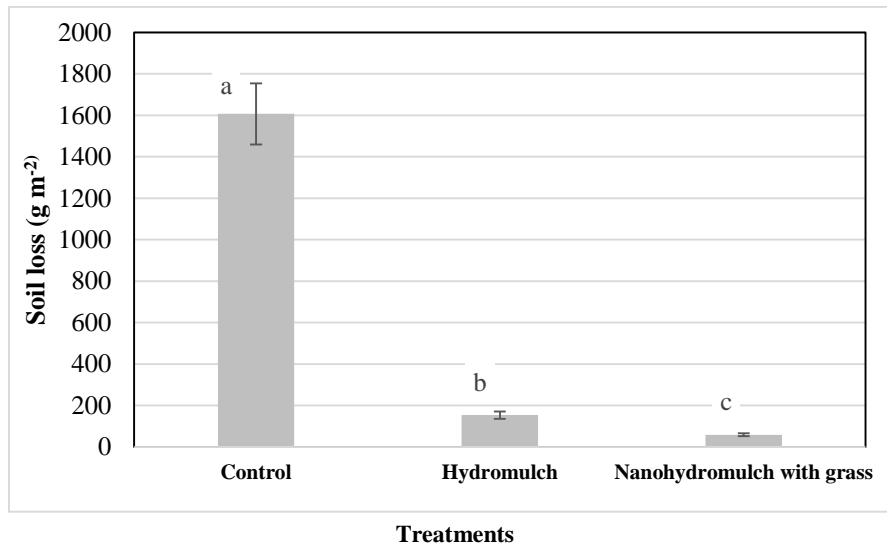


Fig. 10. Effect of two treatments, NBH and SH, on runoff coefficient compared to the control treatment.

Parhizkar *et al.* (2024) concluded in a study that mulches can protect the soil surface by absorbing water and slow down the flow of water on the soil surface. This study showed that hydromulches reduce the speed of runoff flow and thus reduce the potential for soil erosion. Covering the soil with hydromulches, especially in heavy rainfall conditions and on sloping lands, can significantly reduce runoff and prevent soil erosion. However, the results of another study showed that grass vegetation can significantly prevent runoff, since plant roots increase the ability of the soil to absorb water (Liu *et al.* 2023). This feature of grasses reduces the speed of water flow and thus reduces runoff in sloping areas. The reason for the difference between the results of the present study and those of Liu *et al.* (2023) may be related to the short rainfall time and the length of the slope.

### Effect of slope and protection treatments on soil loss

The effect of slope on soil loss was significant ( $p < 0.01$ , Table 1). Soil loss at the 10% slope was  $503 \text{ g m}^{-2}$ , while at the 30% slope increased by 41% to  $711 \text{ g m}^{-2}$ . The effect of protection treatments on soil loss was also significant ( $p < 0.01$ ). The mean comparison of the two hydromulch treatments on soil loss compared to the control is presented in Fig. 11. The highest soil loss was recorded in the control compared to the two other treatments ( $p < 0.01$ ). Afterward, the SH treatment was located. The lowest soil loss was recorded in the NBH with grass treatment ( $p < 0.01$ ).



**Fig. 11.** Effect of two treatments, NBH and SH, on soil loss compared to the control treatment.

According to the results of this study, the combination of NBH with grass exhibited the greatest effect in reducing soil loss compared to other treatments. This combination effectively reduced soil erosion by creating a protective cover and improving soil permeability. Similar studies have shown that the combination of plant covers with nano-mulches can improve soil physical properties and reduce erosion. This combination is very effective by protecting the soil and increasing water absorption capacity, especially in sloping areas that are more prone to erosion (Prosdocimi *et al.* 2016).

### Calculating the cost of implementing different types of hydromulches

Table 2 shows the results of calculating the cost of implementing three types of hydromulch. As the cost comparison results show, SH was able to control runoff and sediment yield despite its low cost compared to the two other treatments. Also, by elevating cost, the protective cover can be improved by adding grass seed. If there is no cost constraint, NBH is recommended along with grass.

**Table 2.** Calculation of the cost of implementing various types of hydromulches for  $1 \text{ m}^2$  (Tomans, 1 Toman = 10 Rials)

Materials	Hydromulch + grass seed	SH	NBH + grass seed
Rice husk	4444.4	4444.4	4444.4
Animal manure	1111.1	1111.1	1111.1
Biochar	166666.7	166666.7	166666.7
Grass seed	222222	-	222222
Starter fertilizer	215555	-	215555
Eremurus	91666	92666	91666
Nano silica	-	-	777777
Total	701665	263888	1479442

### CONCLUSION

The results of this study indicated a significant effect of slope and protection treatments on reducing soil erosion in sloping lands. In particular, the effect of slope on soil loss, sediment yield, and sediment concentration was significant, and by elevating slope, the amount of soil loss and sediment yield increased significantly. On the other hand, the effect of soil types (including soils from cut and fill slopes of forest road, and the soil of the machine-

operating trails) on these factors was not significant in this study, indicating a limited effect of soil characteristics compared to slope and protection treatments under experimental conditions. In this study, using nano-biodegradable hydromulch (NBH), especially in combination with plant covers such as grass, exhibited great positive effects on reducing sediment yield, sediment concentration, and soil loss. The simple hydromulch without vegetation (SH) and NBH treatments reduced sediment by 90% and 96%, respectively compared to the control. NBH with grass treatment showed the lowest amount of soil loss and sediment yield compared to other treatments. These results confirm the effectiveness of NBH in controlling erosion and managing water and soil resources in sloping areas such as forest road sides. Therefore, using these treatments can be considered as an effective solution for soil protection in these conditions. These findings emphasize the importance of using natural protective materials along with plants in reducing damage caused by soil erosion in forest roads. It is essential to clarify that these results are derived from a controlled laboratory scale study. While the results provide valuable proof-of-concept and highlight the potential of NBH as a soil conservation tool, they may not directly translate to field conditions without further validation. Therefore, this study primarily serves to identify promising materials and interactions for erosion control. We recommend field-scale trials under diverse climatic and topographic conditions to validate the performance, durability, and cost-effectiveness of NBH and SH treatments before broad operational recommendations can be made. Future research should also focus on optimizing application methods, assessing long-term ecological impacts, and conducting comprehensive economic analyses comparing these novel materials to traditional erosion management practices. Given the positive results of the present study, it is suggested that these materials be further tested and evaluated in different types of soils and areas with different climatic and geographical characteristics. In addition to NBH, combining these materials with other natural mulches such as sawdust, dry stems, and plant residues can exhibit greater effects on reducing erosion and improving soil structure. The results of a simple economic comparison showed that despite being the most economical option, SH still effectively reduced runoff and sediment yield. Spending more by adding grass seed enhances the protective ground cover further. When budget is not a concern, the best choice is NBH combined with grass. For wider use of NBH on sloping lands, the costs of production, transportation, and installation of these materials need to be compared with the environmental benefits of reducing erosion and improving soil conditions. Therefore, it is necessary to conduct thorough economic studies to evaluate the economic efficiency of using NBH compared to other erosion management methods. Future studies should quantify the cost-effectiveness of NBH in terms of both the erosion reduction per unit of cost and the potential ecosystem service benefits.

#### **Conflict of interest**

There is not any conflict of interest.

#### **Funding declaration**

no Funding.

#### **REFERENCES**

- Abbasi, K, Neyshabouri, M, Oustan, SH & Ahmadi, A 2015, Hydromulch and polyacrylamide effects on runoff control, sediment yield and N, P, K losses in laboratory conditions. *Water and Soil Science*, 24(4): 247-259.
- Abbas, H, Singh, A & Zhang, Z 2021, Soil erosion and sediment transport under different land management practices. *Journal of Soil and Water Conservation*, 76(4): 245-257.
- Dunkerley, D 2014, Vegetation cover and the reduction of soil erosion in arid and semi-arid environments. *Catena*, 115: 23-33.
- Fakhari, MA, Lotalian, M, Hosseini, SAO, Khaledi, D 2018, Effect of rice straw and wood chips on soil erosion and seeding growth on the fill slope forest roads. *Environmental Erosion Research*, 8(2): 104-118.
- Fan, D, Jia, G, Wang, Y, Yu, X 2023, The effectiveness of mulching practices on water erosion control: A global meta-analysis. *Geoderma*, 438: 116643.
- Faucette, LB, Risse, LM, Nearing, MA, Gaskin, JW, West, LT 2004, Runoff, erosion, and nutrient losses from compost and mulch blankets under simulated rainfall. *Journal of Soil and Water Conservation*, 59(4): 154-160.
- Foster, GR & Renard, KG 2002, Soil erosion: Processes, prediction, measurement, and control. Wiley.

- Gomez, JA & Nearing, M A 2005, Runoff and soil erosion as affected by rainfall intensity and soil surface conditions. *Soil Science Society of America Journal*, 69(6): 1893-1900.
- Iran Meteorological Organization 2021, Annual Rainfall Report. [www.irimo.ir](http://www.irimo.ir).
- Iserloh, T, Peter, KD, Fister, W, Wirtz, S, Butzen, V, Brings, C & Ries, JB 2015, Rainfall simulation experiments with a small portable rainfall simulator: Research on runoff generation and soil erosion. *Geophysical Research Abstracts*, 17: 15608p.
- Kader, MA, Singha, A, Begum, MA, Jewel, A, Khan, FH & Khan, NI 2019, Mulching as water-saving technique in dryland agriculture. *Bulletin of the National Research Centre*, 43(1): 1-6.
- Kamphorst, A 1987, A small rainfall simulator for the determination of soil erodibility, Netherlands. *Journal of Agriculture Science*, 35: 407-415.
- Keivan Behjou, F, Mostafazadeh, R, Alaei, N 2024, Effects of forest logging systems on the river flow regime indices using graphical techniques: a case study in a small natural forest. *Hydrology*, 11: 94, <https://doi.org/10.3390/hydrology11070094>.
- Lal, R 2001, Soil degradation by erosion. *Land Degradation & Development*, 12(6): 519-539.
- Li, X, Zhang, L & Liu, J 2022, Effect of hydro-mulch mixtures on soil erosion control and vegetation establishment on sloping lands. *Journal of Environmental Management*, 307: 114452.
- Li, W, Zhang, X, Singh, VP 2023, Relative influence of soil properties, topography, and land cover on soil hydrological processes: A meta-analysis. *Journal of Hydrology*, 625: 130032.
- Liu, Y, Zhang, J, Wang, L & Zhao, Y 2023, How grass cover density regulates surface runoff and soil loss: An experimental assessment under simulated rainfall. *Catena*, 231: 107351.
- Markou, G, Santini, C & Papadakis, E 2007, Rainfall simulation experiments for evaluating soil erosion control measures. *Soil & Tillage Research*, 94(1): 30-39.
- Page, AL, Miller, RH & Keeney DR, 1982, Methods of soil analysis. Part 2: Chemical and microbiological properties. Soil Science of America Madison, Wisconsin, USA.
- Parhizkar, M, Lucas-Borja, ME, Denisi, P, Tanaka, N, Zema, DA 2024, Comparing the effects of hydromulching and application of biodegradable plastics on surface runoff and soil erosion in deforested and burned lands. *Journal of Hydrology and Hydromechanics*, 72(4): 422-435.
- Parhizkar, M, Shabanpour, M, Lucas-Borja, M & Antonio Zema, D 2021, Hydromulch roots reduce rill detachment capacity by overland flow in deforested hillslopes. *Journal of Hydrology*, 598: 112-119.
- Parsakhoo, A & Hosseini, SA 2023a Investigating the effectiveness of different types of conservation treatments in controlling the soil nutrients loss from side slopes of forest roads. *Journal of Water and Soil Conservation*, 30 (2): 141-159.
- Parsakhoo, A & Hosseini, SA 2023b, Effect of bioengineering treatments on reduction of soil erosion from road cut slope and fill slope. *Journal of Forest Science*, 69(9): 367-376.
- Pimentel, D, Harvey, C, Resosudarmo, P, Sinclair, K, Kurz, D, McNair, M, Crist, S, Shpriz, L, Fitton, L, Saffouri, R & Blair, R 1995, Environmental and economic costs of soil erosion and conservation benefits. *Science*, 267: 1117-1123.
- Prosdocimi, M, Tarolli, P & Artemi, C 2016, Mulching practices for reducing soil water erosion: A review." *Earth-Science Reviews*, 161: 191-203.
- Saeidi, M, & Sadeghi, S 2010, Evaluation of soil loss and sediment yield using rainfall simulation tests. *Soil Science Society of America Journal*, 74(1): 20-27.
- Sadeghi, SHR, Sharifi Moghadam, E, & Gholami, L 2014, Effect of rice straw on surface runoff and soil loss in small plots. *Journal of Water and Soil Resources Conservation*, 3(4): 73-83.
- Scherrer, M, Thakur, M & Sharma, S 2020, Hydromulch as an effective tool for improving soil characteristics and promoting plant growth. *Soil Science and Plant Nutrition*, 66(1): 65-75.
- Silva, J, Duarte, A & Oliveira, A 2023, Assessment of sediment transport and soil erosion in response to different hydromulch treatments. *Land Degradation & Development*, 34(2): 358-370.
- Singh, YV 2024, Standard methods for soil, water and plant analysis. CRC Press.
- Smith, J, Brown, K & Davis, L 2020, Scale-dependency of factor interactions in watershed hydrology: A meta-analysis. *Water Resources Research*, 56(8), e2020WR027891. DOI: 10.1029/2020WR027891.

- Solgi, A Naghdi, R, Zenner, E, Hemmati, V, Behjou, F & Masumian, A 2021, Evaluating the effectiveness of mulching for reducing soil erosion in cut slope and fill slope of forest roads in Hyrcanian forests. *Croatian Journal Forest Engineering*, 42(2): 259-268.
- Sprague, CJ & Prellwitz, SG 2020, Performance and cost-effectiveness of hydromulching for erosion control on construction slopes. *Journal of Environmental Management*. 276: 111288.
- Walkley, A & Black, IA 1934, An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37: 29-38.
- Wischmeier, WH 1976, Use and misuse of the universal soil loss equation. *Journal of Soil and Water Conservation*, 31(1): 5-9.
- Zhang, G-H, Wang, L-L, Tang, K-M, Luo, R-T & Zhang, X-C 2014, Effects of vegetation cover and rainfall intensity on sediment-bound nutrient loss, size composition and volume fractal dimension of sediment particles. *Pedosphere*, 24(5): 613-625, DOI: 10.1016/S1002-0160(14)60047-9.
- Zhang, X, Liu, J & Liu, H 2020, Effect of vegetation cover on soil erosion and sediment transport under different rainfall intensities. *Journal of Hydrology*, 583: 124611.
- Zhao, L, Zhang, X & Wu, X 2023, Effect of soil physical and chemical properties and slope on sediment yield and runoff: A rain simulation approach. *Environmental Earth Sciences*, 82(2): 456-470.