



## Efficacy of nano-hydromulch in mitigating runoff and sediment from forest road trenches

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### ABSTRACT

Water erosion causes significant damage to forest roads. Protecting cut-and-fill slopes can mitigate these damages. This study aimed to evaluate the effectiveness of several protective coverings based on nano-materials in reducing runoff and sediment yield from forest road trenches. Nano-hydromulch (NH) with rice straw, sawdust and grass, NH with grass, grass, and control were investigated under laboratory conditions on slopes of 10% and 30%, as representatives of the major slopes of forest road trenches, with three replications. Using a rainfall simulator, a rainfall event with a volume of 1800 cm<sup>3</sup> was simulated, and runoff, sediment, sediment concentration, runoff coefficient, and soil loss were measured in the treatments. Results indicated that increasing slope steepness from 10 to 30% significantly increased runoff by 76%, sediment yield by 979%, and soil loss percentage by 480% ( $p < 0.01$ ). Therefore, cut-and-fill slopes should be adequately protected. NH treatments effectively reduced runoff, and by creating proper soil aggregate adhesion, reduced substantially sediment yield and soil loss ( $p < 0.01$ ). It is recommended to use NH, especially combined with grass, to protect cut-and-fill slopes of forest roads, thereby reducing maintenance costs.

**Keywords:** Grass, Rainfall simulator, Sediment concentration, Soil loss.

**Article type:** Research Article.

### INTRODUCTION

Erosion is the process through which soil particles are detached from their original location and transported to another site by a transferring agent (Lal & Stewart 2018; Morgan 2020). The role of erosion and sediment production in soil fertility loss, reservoir siltation, clogging of irrigation channels, waterways, and rivers, river water turbidity, water quality degradation, and pollution of downstream water bodies has long been recognized by geoscience experts (Pimentel *et al.* 2019; Zhang *et al.* 2020b). Soil erosion is also a major challenge in natural resource and environmental management. Runoff, the flow of rainwater that fails to infiltrate the soil, rapidly moves downstream, intensifying soil erosion (Liu *et al.* 2021). Furthermore, alterations to natural slope profiles caused by cut-and-fill activities during forest road construction disrupt soil hydraulic behavior and physical-chemical properties, leading to increased soil loss and mass movement (Brown & Burnham 2022). Numerous studies have addressed soil erosion control and runoff reduction (Nguyen *et al.* 2023a, b). Moreover, mechanical and biological methods for reducing soil erosion have garnered significant attention (Zhang *et al.* 2022a). For example, in a study by Yakupoglu *et al.* (2019), the potential benefits of polymers in controlling soil erosion for agricultural projects were investigated. The results indicated that while polymers did not delay the initiation of runoff, they effectively reduced total runoff, sediment yield, and soil displacement caused by splash erosion. Therefore, to prevent or mitigate the aforementioned effects, it is necessary to plan and implement soil



conservation and sediment control measures within the framework of watershed management projects. This approach can achieve more favorable outcomes by utilizing innovative methods, particularly bioengineering techniques (Kumar *et al.* 2021; Wang *et al.* 2022b). The benefits of using biological soil conservation methods and bioengineering techniques for stabilizing and rehabilitating unstable soils and slopes with vegetation challenges have been well-documented (Greenway 2019). One such bioengineering method employed to address soil erosion issues and minimize its negative impacts is hydromulching treatments, which continue to evolve and improve in effectiveness (Zhang *et al.* 2023; Chen *et al.* 2023a). Previous research has demonstrated that the application of various mulches can significantly reduce soil erosion and runoff. Mulches are recognized as a biological method for reducing soil erosion and enhancing water infiltration (Blanco-Canqui & Ruis 2020). By covering the soil surface, mulches prevent water evaporation and help maintain soil moisture. However, traditional mulches, such as rice straw or sawdust, have limitations, including high costs, the need for continuous maintenance, and environmental impacts, such as fire risks, especially in forested areas (Morgan & Nearing 2022). Despite these benefits, there are key limitations in the performance and effectiveness of bioengineering methods and hydromulching. First: The limitation of re-establishment and plant growth, which requires time (Brown & Burnham 2022). Second: The quality of hydromulches can affect their performance. Using old or low-quality materials may lead to poor results. Third: Bioengineering methods and hydromulches require specific conditions, such as temperature, humidity, and soil type. Under unfavorable conditions, their performance can decrease (Zhao *et al.* 2019). Fourth: Long-term costs—while initial installation may be cost-effective, maintenance and material renewal costs can be high (Gagg & Cooper 2020). Fifth: The risk of fire, particularly in forested areas and dry regions, when using plant fibers and jute nets, which are easily flammable and increase the risk of fire (Alvarez & Carpintero 2023). In addition to all these mentioned issues, due to global warming and climate change, we are experiencing heavy rainfall events (O'Gorman, 2019; Milly *et al.* 2020; Trenberth 2022). For this reason, the necessity of finding innovative and efficient methods for controlling soil erosion is more pressing than ever. In this research, unlike previous studies where rainfall intensity was low, the effects of heavy rainfall have not been thoroughly examined, nor has the application of nanomaterials in the creation of hydromulch to prevent erosion and soil loss been explored. Additionally, there has been a lack of comprehensive research on NHs. This study aims to examine soil erosion control and surface runoff using nanomaterials and the development of nano-based hydromulch, along with evaluating its economic and practical benefits—an area that has not been previously explored in research and practice (Chen *et al.* 2023b; Zhang *et al.* 2024). Nanotechnology, particularly using Nano-hydromulch (NH), has proven to be an innovative method that significantly contributes to soil stabilization and erosion reduction (Zhang *et al.* 2021a; Li *et al.* 2022). This research aims to fill the gaps in previous studies, particularly those that focused solely on normal and low-intensity rainfall. It investigates the effects of NH and its combination with super sport grass seed, highlighting the economic and environmental advantages of this method over traditional approaches (Gupta & Sharma 2023). The main reason for selecting super sport grass seed along with NH, instead of native plants, is the rapid establishment of the super sport grass within a 10 to 14-day period, which is a significant advantage (Zhang *et al.* 2022b). The overall benefits of this choice include rapid grass growth. Moreover, the presence of NH accelerates this growth and enhances root development, leading to quicker soil coverage and prevention of erosion (Gupta *et al.* 2022). Additionally, this type of grass is highly resistant to various environmental conditions, including heat, cold, drought, and heavy traffic (Singh *et al.* 2022). Furthermore, since this type of grass requires minimal maintenance and can grow well with minimal cost and effort, it improves soil quality as the roots of the super sport grass enhance soil structure and increase the activity of beneficial microorganisms in the soil, contributing to soil quality improvement (Jiang *et al.* 2023). All of these factors create favorable conditions for the growth of other native plants in the area following the establishment of the grass. The successful implementation of this method and innovation has proven, unlike previous studies and research, the expansion of bioengineering techniques and optimal use of local resources to combat soil erosion, especially in critical conditions (such as 1800 cm<sup>3</sup> of rainfall lasting 12 minutes, which can cause a massive flood with high erosion volume, particularly in erosion- and landslide-prone areas). Moreover, the use of this technique is more cost-effective than mechanical methods and requires less heavy equipment, such as loaders and excavators. This aspect is crucial for road protection and maintenance, especially in forestry projects that often face financial and even environmental constraints (Lal & Stewart 2018; Morgan, 2020; Zhang *et al.* 2021b). The general advantages of using NH include increased soil adhesion and strength. The nanoparticles in NH enhance the adhesion of soil particles to each other, which helps reduce both wind and water erosion and protects plants

from stress caused by environmental conditions (Li *et al.* 2022; Raza *et al.* 2023). Additionally, NH can improve water permeability in the soil, reducing surface runoff and increasing the recharge of groundwater resources (Thompson *et al.* 2021). Reducing evaporation and retaining moisture are other benefits of NH, as the nanoparticles reduce water evaporation from the soil surface, especially in dry and semi-dry regions (Shao *et al.* 2020). Nanotechnology, by providing nanoparticles with unique properties, has significant potential in improving soil and water management methods. Due to their high specific surface area and unique physical and chemical capabilities, nanoparticles can have a greater impact on reducing soil erosion and runoff. Although there is limited research on using nanoparticles to reduce soil erosion and runoff, initial results have been promising. For example, research has shown that nanoparticles can prevent soil erosion by increasing soil adhesion and improving soil structure (Zhang *et al.* 2021b). They can also help retain soil nutrients, prepare a suitable bed for the re-growth of native plants, preserve soil microorganisms, and increase the resistance of road structures with minimal costs. Additionally, the nanoparticles in the created hydromulch can enhance the resistance of plants and soil to adverse environmental conditions such as heat, cold, and drought (Wang *et al.* 2022c). Using NH also has environmental advantages over traditional methods, including water conservation and reduced runoff, which enhances water infiltration into the soil and replenishes groundwater resources (Brown & Burnham 2022). The preservation of biodiversity is another benefit, as combining NH with super sport grass seeds helps maintain and strengthen the region's biodiversity (Smith & Johnson, 2022). This contributes to improving the environmental status of the area and preserving plant and animal species. Moreover, it helps reduce water pollution by decreasing soil erosion and sedimentation, leading to reduced pollution of both surface and groundwater, which improves water quality and alleviates environmental problems caused by water contamination (Lal 2020). In these conditions, using this method, which is part of bioengineering practices, can also be effective in stabilizing soil on road excavation embankments (Stokes & Morgan 2019). One of the key questions in forest bioengineering is how to select the most efficient method for reducing erosion and sedimentation. Previous studies have shown that traditional mulches such as rice straw and sawdust can help reduce soil erosion and increase soil permeability (Wang *et al.* 2022a), but these methods have limitations, including high costs, maintenance requirements, and environmental impacts. Therefore, we hypothesized that creating NH could overcome these limitations and provide greater efficiency. To test this hypothesis, the effect of NH combined with grass seed was tested under an 1800 cm<sup>3</sup> rainfall on slopes of 10% and 30%. The general objective was to investigate the effect of NH on soil erosion control and surface runoff reduction.

## MATERIALS AND METHODS

The soil used for testing was collected from the Blourdekan forest area in the 27<sup>th</sup> watershed of Langarud, with coordinates 50°04'47" and 37°00'05", located in Guilan Province, Northwest Iran (Fig. 1). The soil was transferred to the laboratory for further examination. For optimal grass growth, the cultivation bed was prepared by combining forest soil with sand. The bulk densities of the forest soil and sand were determined to be 1.3 and 1.6 g cm<sup>-3</sup>, respectively. The natural forest soil of the study area is indeed characterized by a bulk density of approximately 1.3 g cm<sup>-3</sup> and a clay-rich texture with low permeability. However, in controlled laboratory experiments, using fully natural forest soil poses several methodological challenges, including high heterogeneity, strong aggregation, variable organic matter content, and inconsistent moisture and compaction levels, all of which can significantly affect the repeatability and accuracy of hydrological measurements. To overcome these limitations and ensure standardized, reproducible, and comparable test conditions across all treatments, a portion of sand was added to the collected soil. This adjustment was not intended to alter the nature of the soil but rather to:

Reduce excessive aggregation of the clay-rich forest soil,

Achieve uniform compaction and infiltration conditions across replications,

Control initial bulk density to minimize experimental variability, and

Ensure proper function of the rainfall simulator and runoff collection system.

Importantly, even with the sand amendment, the soil maintained its heavy-textured characteristics and low permeability, meaning that the hydrological behavior still realistically represents forest road trench soils, where compaction and low infiltration are common. This approach is consistent with standard soil preparation methods used in laboratory erosion studies (e.g., Angulo-Martínez *et al.* 2012; Hashemi *et al.* 2016), which frequently modify natural soils to ensure homogeneity while preserving the dominant characteristics of the original texture. After preparation, the forest soil and sand were air-dried in the laboratory and passed through a 2-mm sieve. A total of 600 g of forest soil and 600 g of sand were uniformly mixed and placed in an experimental tray. The

mixture was then evenly spread using a plastic spatula, and the necessary experiments were conducted on this substrate (Tajada & Gonzalez 2007; Sadeghi *et al.* 2019).



**Fig. 1.** The location of study area in the north of Iran.

The experimental treatments included: (i) Nano-hydromulch (NH) with rice straw, sawdust, and grass, (ii) NH with grass, (iii) grass, and (iv) control treatment. The experiment was conducted using 12 experimental plots (rice seedling trays), with slopes of 10% and 30%, and three replications, totaling 24 experimental units. Choosing the 10% and 30% slopes was to evaluate the performance of NH under controlled laboratory conditions that represent slope categories commonly found in forest road environments. Studies on forest road design and maintenance indicate that slopes of 10–12% are typically considered low-risk and stable, whereas slopes around 30% often represent the threshold at which instability increases and runoff and surface erosion become more pronounced. Therefore, these two slope gradients were chosen to represent both a low-risk and a relatively critical condition. This selection allowed us to accurately analyze both the main effect and the interaction effect of slope  $\times$  protective treatment within the experimental design (ANOVA), while maintaining fully controlled and repeatable laboratory conditions. For this phase of the research, rice seedling trays with dimensions of  $0.25 \times 0.25$  m and a depth of 0.07 m were used. The components of NH in the experimental plots were prepared by mixing the following substances: 1.2 g superabsorbent, 0.7 g NPK, 0.45 g superhumic acid, 0.25 g nano chelated green solid,  $1 \text{ cm}^3$  liquid silica nano-fertilizer, 18 g starch adhesive,  $1 \text{ cm}^3$  surfactant, 10 mg silica nanoparticles, and 18 g grass seed in 150 mL distilled water, which was then sprayed onto the surfaces of the experimental plots using the hydroseeding method (Lyu *et al.* 2021).

For this phase of the research, the following products were used:

Super-humic product from Labin, Spain;

Surfactant liquid fertilizer from Barcelos, Portugal;

Starch adhesive from Merck, Germany;

Silica nanoparticles (Silicium Oxide-Amorphous SiO<sub>2</sub> 99.99% 4N High Purity Powder) from MSE Supplies, USA;

Nano-hydrogel from Nanosazan Javan Company, Iran;

NPK 20-20-20 fertilizer from WOPROFERT, Netherlands;

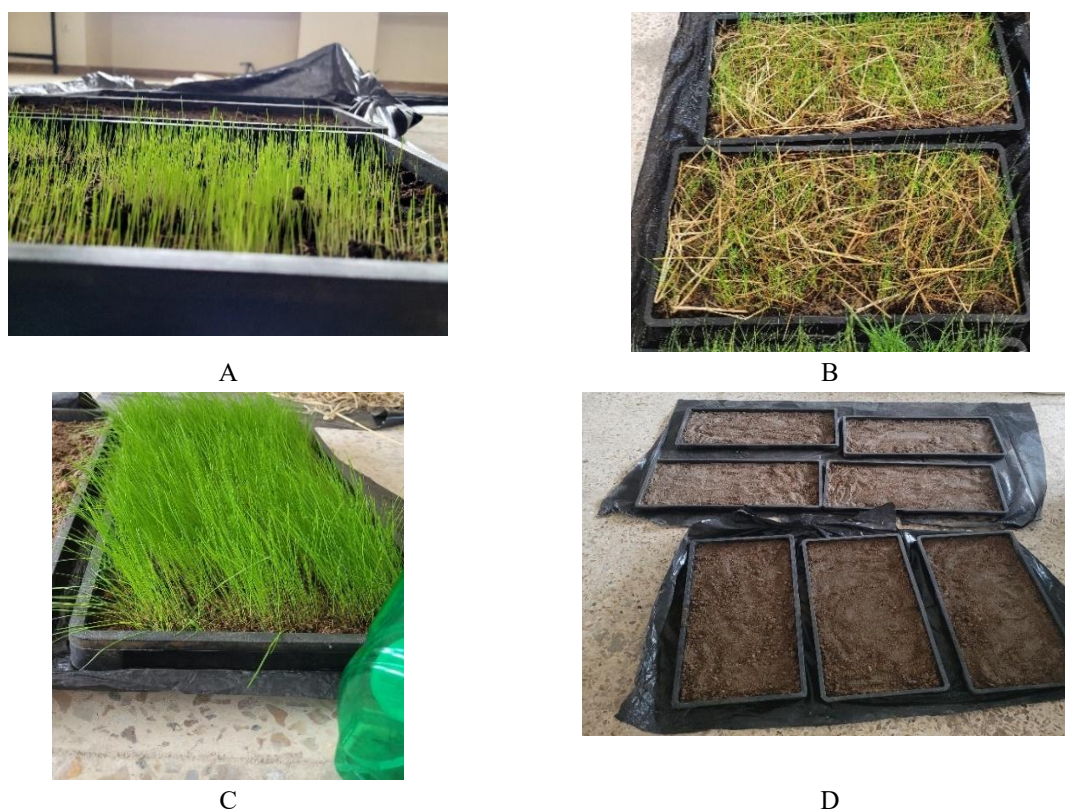
Nano-micro fertilizer in solid form from Chelated Khazra Company, Iran;

Liquid silica nano-fertilizer from SHOCK, USA

Dutch Four Seed Super Grass variety was selected for the grass seed.

In this study, we used porous, hydrophilic silica nanoparticles (SiO<sub>2</sub>) with a particle size of 15–20 nm, pore size of 2–6 nm, bulk density of 2.4 g cm<sup>-3</sup>, specific surface area of 640 m<sup>2</sup> g<sup>-1</sup>, purity of 99.5%, and hydroxyl content > 45%. These nanoparticles were produced using the CVD plasma method in the USA. Mechanistically, the uniform dispersion of these nanoparticles within the hydromulch enhances soil particle cohesion, stabilizes soil aggregates, increases water retention, and reduces the kinetic energy of raindrops, thereby decreasing splash erosion and sediment detachment. The concentration of nanoparticles used was optimized to ensure effective soil stabilization while maintaining workability and adhesion of the hydromulch (Fine-nano 2025). We acknowledge that the potential environmental impacts of nanoparticles should be considered. Although the small-scale laboratory study allows precise evaluation of their effect on runoff and sediment yield, field-scale studies and long-term monitoring are necessary to fully assess ecological safety and potential environmental risks associated with nanoparticle application. In the laboratory conditions, the research was conducted as follows: First, each material required for the preparation of the hydromulch composition was measured using a digital scale with an accuracy of 0.0001 g. Then, the materials were mixed in a graded cylinder by adding distilled water to reach the required volume, and the mixture, along with the grass seed, was sprayed evenly onto the experimental plots using a manual mixer. For the treatment involving straw and rice husk, 0.5 g rice husk and 0.5 g straw and rice husk mixture were spread over the soil surface in the experimental plots after spraying the grass seed (Fig. 2; Zhang *et al.* 2020a). For the only grass treatment, 18 g grass seed were evenly spread over the soil in the seedbed tray, and a control treatment without any protective cover was prepared with a mixture of sand and forest soil (Fig. 2). Under controlled laboratory conditions (18 to 25 °C) with a combined lighting regimen (artificial and natural), the super sport grass reached significant vegetative growth, reaching an average height of 15 cm in 14 days, with regular irrigation via spraying. The irrigation was applied alternately (daily during the first week and every other day during the second week). To simulate rainfall, a portable rainfall simulator was designed and developed at the Soil Conservation and Watershed Management Research Institute, Iran (Wischmeier & Smith 1978; Fig. 3). The simulator used in this study was based on the Kamphorst standard model available at Wageningen University, the Netherlands, and was adapted for a plot size of 0.06 m<sup>2</sup> (25 cm × 25 cm). This device is lightweight and easy to transport. The rainfall simulator was positioned at a height of 55 cm above the soil surface to ensure a uniform and realistic rainfall distribution over the experimental plots (Wischmeier & Smith 1978). This height was selected based on previous laboratory studies (e.g., Kavian *et al.* 2010) to balance drop size, impact energy, and coverage area, simulating natural rainfall intensity while avoiding splash erosion artifacts that could occur at lower heights. The rainfall simulator consists of three main components: a sprinkler with a pressure regulator to create a standardized rainfall pattern, a base, and a metal frame. The simulator is particularly suitable for assessing soil erosion characteristics, water infiltration rates, and soil conservation research. Its application is considered a standard method for determining the erodibility of surface deposits in field studies. Each treatment was tested in three replications (Saeidi & Sadeghi, 2010; Wang *et al.* 2022c) using a rainfall simulator with a precipitation volume of 1800 cm<sup>3</sup>. This study was conducted in the controlled environment of the Pressurized Irrigation Laboratory at the University of Guilan, allowing precise monitoring of runoff, soil loss, and data collection (Miyata *et al.* 2009; Ghahramani *et al.* 2011; Li *et al.* 2021). For this stage of the research, a hand-crafted stainless-steel V-shaped gutter was attached to the lower edge of the trays containing grass to direct runoff and sediment into a collection container. The total volume of runoff and sediment collected after each rainfall simulation from the experimental plots was measured and weighed (Markou *et al.* 2007; 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

sediment. Total soil loss was also determined using the on-site placement method (Saeidi & Sadeghi 2010; Abbas *et al.* 2021).



**Fig. 2.** Protective treatments prepared in the present study; A: NH with grass seed, B: NH with straw, rice husk, sawdust, and grass; C: grass; and D: control.



**Fig. 3.** Usage of the rainfall simulator in the laboratory conditions.

The data collected for this study included soil loss, runoff volume, and sediment yield. To estimate the runoff coefficient, the total runoff volume generated during the experiment was divided by the total rainfall volume received by the plot surface over the same period. Parameters analyzed in this study included runoff volume, sediment yield, sediment concentration, runoff coefficient, and soil loss. The study was designed as a factorial experiment with two main factors: protective treatments at four levels and slope at two levels (10% and 30%), with three replications for each combination. Laboratory data were analyzed using SPSS software. Analysis of

variance (ANOVA) was performed, and if significant differences were identified, mean comparisons were conducted using Tukey's method.

## RESULTS

The analysis of variance for protective treatments under two slope gradients (10% and 30%) is presented in Table 1. The slope significantly affected runoff volume, sediment yield, sediment concentration, and runoff coefficient at the 1% probability level, while soil loss percentage was significant at the 5% level.

The protective treatments significantly influenced runoff volume, sediment yield, sediment concentration, runoff coefficient, and soil loss percentage, all at the 1% probability level. The interaction between slope and protective treatments was significant for runoff volume, sediment yield, and sediment concentration at the 1% level, and for runoff coefficient at the 5% level, but it did not significantly affect soil loss percentage.

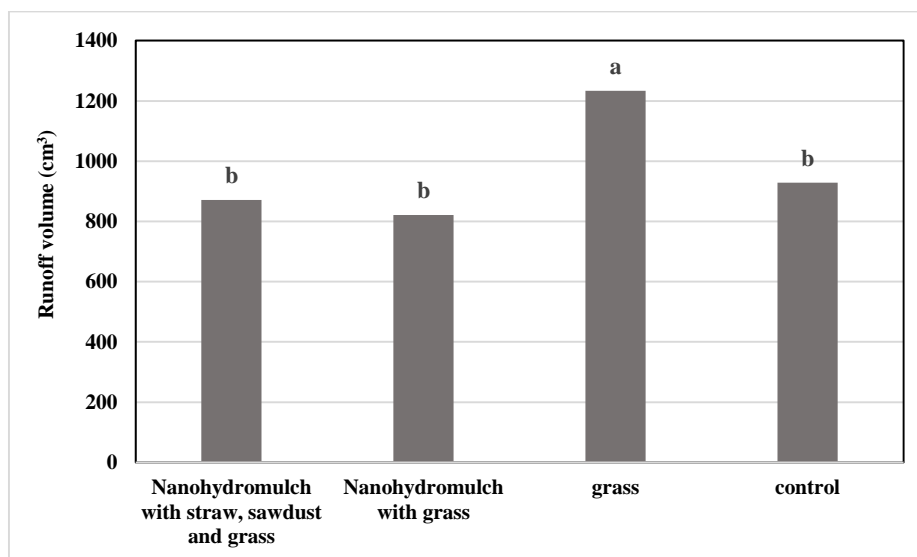
**Table 1.** Analysis of variance for the effects of slope and protective treatments on runoff, sediment yield, sediment concentration, runoff coefficient, and soil loss percentage.

Source of variation	df	Mean square				
		Runoff	Sediment yield	Sediment concentration	Runoff coefficient	Soil loss percentage
Slope	1	1680104**	59.4**	25.4**	0.55**	0.936*
Error A	4	42758	0.887	0.731	0.01	0.362
Protective treatment	3	205193**	159.6**	150.3**	0.07**	11.3**
Slope × protective treatments	3	65449**	54.5**	25.5**	0.02*	0.47 <sup>ns</sup>
Error B	4	42758	0.88	0.58	0.005	0.165

Note: ns: not significant, \*: significant at 5% level, \*\*: significant at 1% level.

### Effects of slope and protective treatments on runoff volume

The effect of slope on runoff volume was significant ( $p < 0.01$ ). The collected runoff volume at a 10% slope was 699 cm<sup>3</sup>, while at a 30% slope, increased by 76%, reaching 1228 cm<sup>3</sup>. The effect of protective treatments on runoff was also significant ( $p < 0.01$ ). The comparison of mean runoff volumes in different protective treatments is presented in Fig. 4. The highest runoff volume was observed in the grass treatment compared to the others ( $p < 0.01$ ). Other treatments showed no significant differences in runoff volume, although the lowest was recorded in the nano-hydromulch + grass.



**Fig. 4.** Effect of different protective treatments on runoff volume compared to the control treatment.

The comparison of the mean interaction between slope and different protective treatments on runoff volume is shown in Fig. 5. The highest runoff volume was recorded in the grass protective treatment at a 30% slope compared to other ones ( $p < 0.01$ ). However, the lowest was observed in the control at a 10% slope.

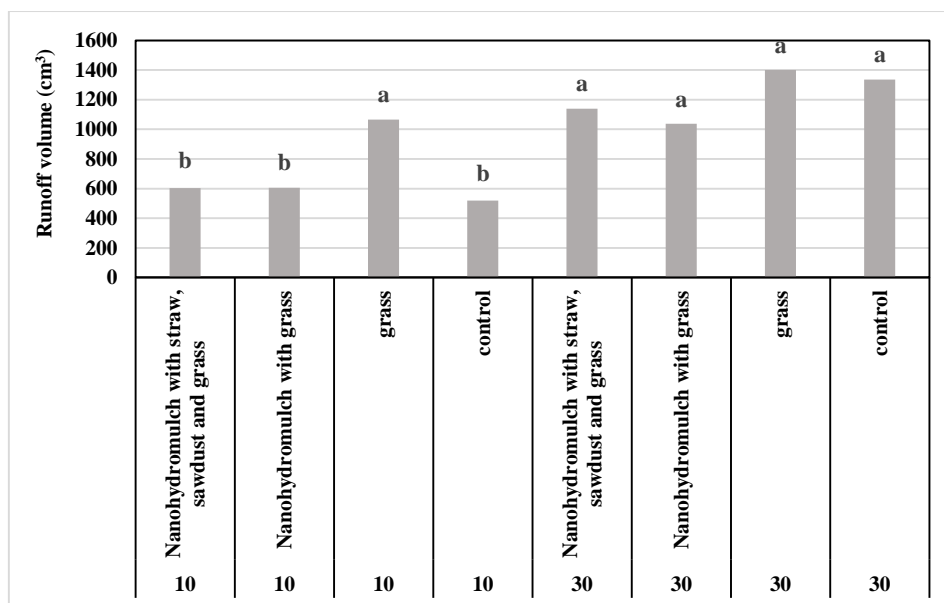


Fig. 5. Interaction effect of slope and different protection treatments on runoff volume compared to the control treatment.

### The effect of slope and protective treatments on the sediment yield

The effect of slope on the sediment yield was significant ( $p < 0.01$ ). The sediment weight at a 10% slope was 6.7 g, while at a 30%, it increased nearly tenfold to 72.3 g. The elevation in slope results in higher runoff speed and, consequently, reduced soil aggregate stability. The effect of protective treatments on sediment production was also significant ( $p < 0.01$ ; Fig. 6). The highest sediment production was observed in the control treatment compared to the others ( $p < 0.01$ ). There was no significant difference among the other treatments, although the least was recorded in Nano-hydromulch (NH) + grass.

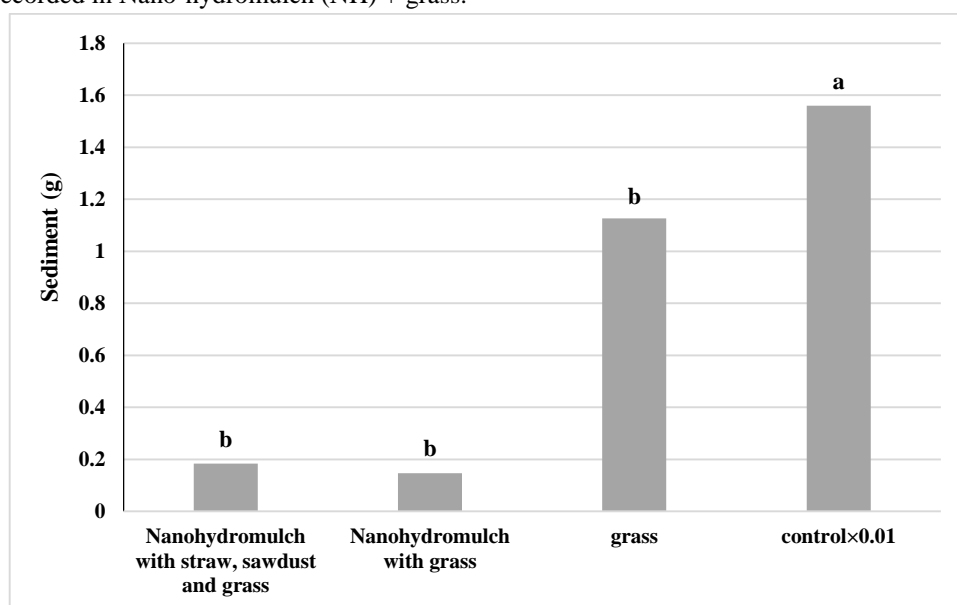


Fig. 6. Effect of different protective treatments on the sediment yield compared to the control.

The interaction effect of slope and different protective treatments on sediment production is shown in Fig. 7. The highest sediment production was observed in the control at the 30% slope, followed by the control at the 10% slope, compared to other treatments ( $p < 0.01$ ). There were no significant differences among the other treatments, although the least was recorded in the NH + straw and sawdust + grass at the 30% slope.

### Effects of slope and protective treatments on sediment concentration

The effect of slope on sediment concentration was significant ( $p < 0.01$ ). At the 10% slope, the sediment concentration was  $11.3 \text{ g L}^{-1}$ , while at the 30%, it increased almost fourfold to  $54.2 \text{ g L}^{-1}$ . The effect of protective treatments on sediment concentration was also significant ( $p < 0.01$ ). A comparison of the mean effects of different

protective treatments on sediment concentration is presented in Fig. 8. So that, the highest was observed in the control treatment compared to the others ( $p < 0.01$ ). There were no significant differences among the other treatments, although the lowest was recorded in the NH + grass.

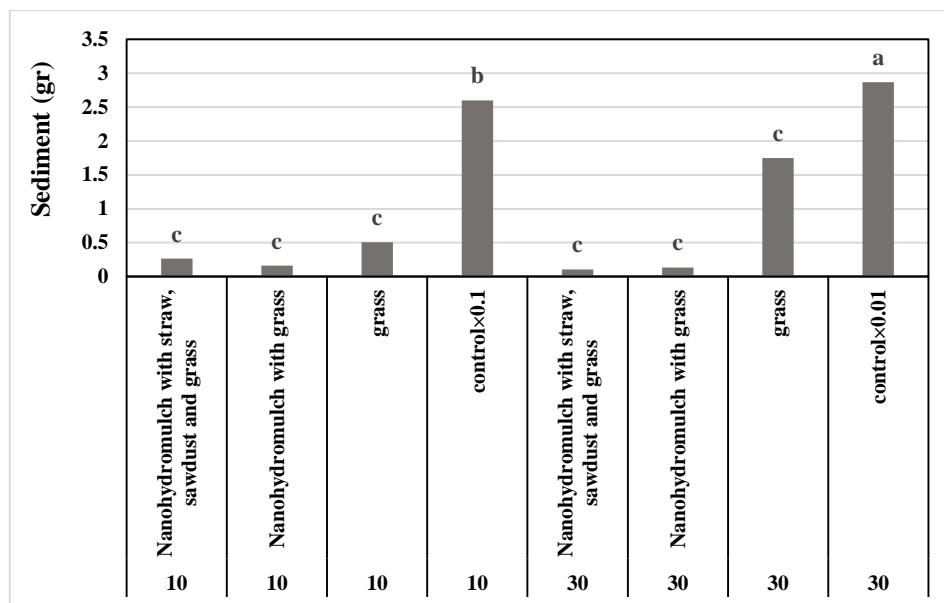


Fig. 7. Interaction effect of slope and different protective treatments on sediment produced compared to the control treatment.

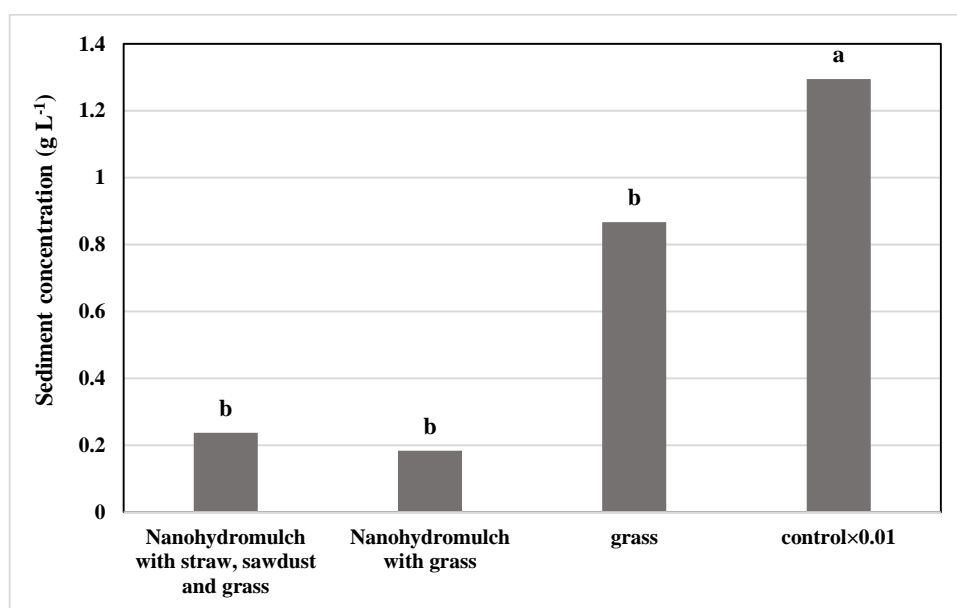


Fig. 8. Effect of different protective treatments on sediment concentration compared to the control treatment.

The comparison of the mean interaction effect of slope and different protective treatments on sediment concentration is presented in Fig. 9. The highest sediment concentration was observed in the control treatment at the 30% slope compared to the others ( $p < 0.01$ ) followed by the control treatment at the 10% slope. There were no significant differences among the other treatments, although the lowest was recorded in the NH + straw, sawdust, and grass at the 30% slope.

**Effects of slope and protective treatments on the runoff coefficient**

Effect of slope on the runoff coefficient was significant ( $p < 0.01$ ). At the 10% slope, the runoff coefficient was 0.4, while at the 30% slope, it increased by 75% to 0.7. Comparison between the mean effects of different protective treatments on the runoff coefficient is presented in Fig. 10. The highest coefficient was observed in the grass treatment, while the lowest in the NH + grass.

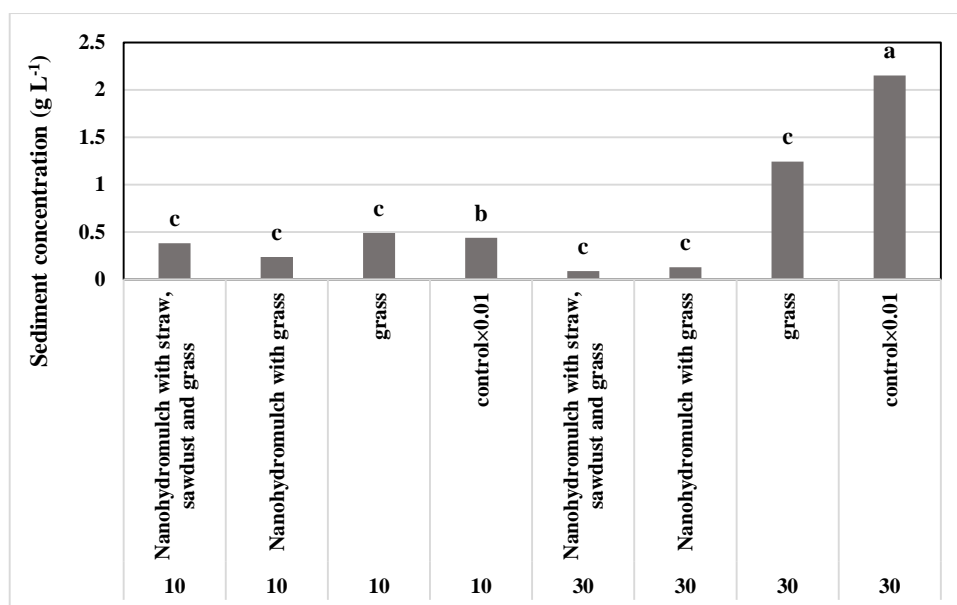


Fig. 9. Interaction effect of slope and different protection treatments on the concentration of sediment produced compared to the control treatment.

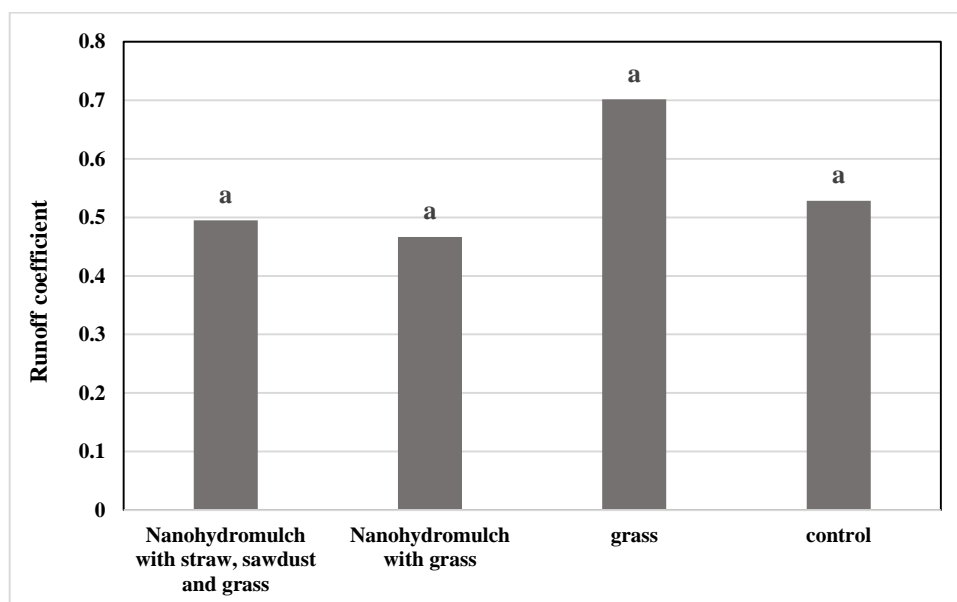


Fig. 10. Effect of different protection treatments on runoff coefficient compared to the control treatment.

Comparison between the mean interaction effect of slope and protective treatments on the runoff coefficient is shown in Fig. 11. The highest runoff was observed in the grass treatment at the 30% slope ( $p < 0.01$ ), followed by 10% slope + NH + grass, NH + straw, sawdust + grass, and the control ( $p < 0.01$ ).

#### Effects of slope and protective treatments on soil loss rate (%)

Effect of slope on soil loss rate (%) was significant at the 1% significant level. At the 10% slope, soil loss was 2.2%, while at the 30%, it increased over tenfold to 24%. The effect of protective treatments on soil loss was also significant ( $p < 0.05$ ). The mean comparison between different protective treatments regarding soil loss is illustrated in Fig. 12. The results clearly demonstrate the critical role of the treatments in mitigating soil erosion under varying slope conditions.

The highest rate of soil loss was recorded in the control treatment compared to the others ( $p < 0.01$ ), followed by the grass treatment, while other treatments showed no significant differences. However, the lowest soil loss was observed in the NH + with grass ( $p < 0.01$ ). The interaction between slope and protective treatments on soil loss was not statistically significant ( $p > 0.05$ ).

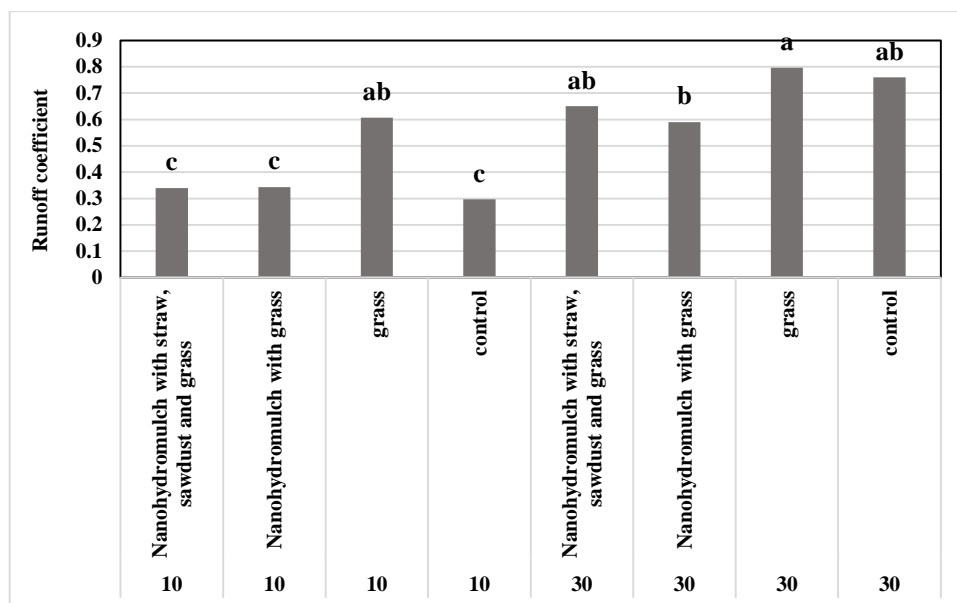


Fig. 11. Interaction effect of slope and different protection treatments on runoff coefficient compared to the control treatment.

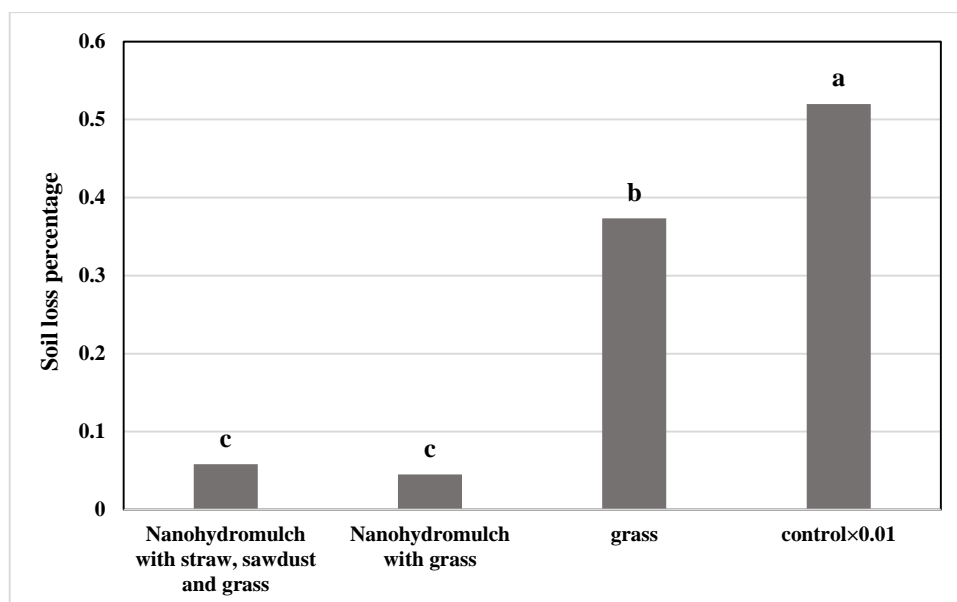


Fig. 12. Interaction effect of slope and different protection treatments on percentage of soil loss compared to the control treatment.

**DISCUSSION**

This study aimed to evaluate the effectiveness of several protective coverings based on nano-materials in reducing runoff and sediment yield from forest road trenches. The slope significantly affected runoff volume and sediment yield, sediment concentration, runoff coefficient, and soil loss. These results align with those reported by Jabbari *et al.* (2022), demonstrating the impact of slope on the studied factors. The interaction between slope and protective treatments was significant for runoff volume, sediment yield, sediment concentration, and runoff coefficient, but it did not significantly affect soil loss. These findings are in accordance with the results of Ricks *et al.* (2020), emphasizing the positive role of hydromulch in reducing soil loss.

**Effects of slope and protective treatments on runoff volume**

The effect of slope on runoff volume was positive. Furthermore, the effect of protective treatments on runoff was significant. The lowest runoff volume was recorded in the Nano-hydromulch (NH) + grass treatment. Ricks *et al.* (2020) reported that hydromulch increases the water retention capacity of soil, reduces the kinetic energy of raindrops, and consequently decreases splash erosion and the breakdown of soil aggregates. The highest runoff

volume was recorded in the grass protective treatment at a 30% slope compared to other treatments, whereas the lowest runoff volume was in the control treatment at a 10% slope.

#### **Effects of slope and protective treatments on sediment amount**

The effect of slope on the produced sediment was positive. As the slope increases, the speed of water movement elevates and the stability of the soil aggregate decreases, resulting in soil separation and upraised sedimentation. As a result, the transport capacity of soil particles increases, leading to a higher sediment production and soil erosion. The effect of protective treatments on sediment production was considerable. The highest sediment production was observed in the control treatment, whereas the least was in the NH + grass. The materials in hydromulch increase the cohesion of soil particles, thus reducing sediment production (Ricks *et al.* 2020). Prats *et al.* (2016) reported that the use of hydromulch could reduce sediment production by over 80%. The highest sediment production was observed in the control treatment, while the least was in the NH + straw and sawdust + grass. Straw and sawdust, due to their porous nature, possess a high water retention capacity and can absorb some of the rainfall, thus reducing runoff volume. These materials increase soil resistance, preventing particle loosening and separation, which in turn reduces sediment production (Farhoudi *et al.* 2018).

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

The effect of slope on sediment concentration was positive and that of protective treatments was significant. The highest sediment concentration was observed in the control treatment, while the lowest was in the NH + grass. The presence of straw and sawdust on the soil surface creates a protective layer compared to the control treatment, reducing the impact of raindrop strikes and, consequently, splash erosion which is the initial trigger for deeper erosion processes and soil particle movement (Angulo-Martínez *et al.* 2012).

#### **Effects of slope and protective treatments on the runoff coefficient**

The effect of slope on the runoff coefficient was positive. The highest coefficient was observed in the grass treatment, whereas the lowest was in the NH + grass. The materials used in protective treatments have a lower bulk density than soil, increasing soil permeability and reducing the runoff coefficient (Farhoudi *et al.* 2018).

#### **Effects of slope and protective treatments on soil loss rate (%)**

The effect of slope on soil loss rate (%) was considerable. The effect of protective treatments on soil loss was also significant. These results align with Mahaske *et al.* (2019), which found a direct relationship between slope steepness and increased soil loss. The results clearly demonstrate the critical role of protective treatments in mitigating soil erosion under varying slope conditions. The highest soil loss was recorded in the control treatment, while the lowest was in the NH + grass. These results are consistent with the findings of Ricks *et al.* (2020), highlighting the positive role of NH in reducing soil loss. Protective treatment materials, due to their high porosity and water retention capacity, absorb a portion of rainfall and reduce runoff volume. These materials enhance soil stability, preventing detachment and dispersion of soil particles, thereby reducing sediment production and soil loss (Farhoudi *et al.* 2018). In the control and grass treatments, where the adhesive properties of NH are absent, soil aggregates are disrupted by raindrop impact (splash erosion) and carried away by runoff. In contrast, treatments containing NH experience reduced raindrop impact, leading to lower soil loss (Ricks *et al.* 2020).

Finally, because of rain simulator dimensions, the used trays in this study with dimensions of  $0.25 \times 0.25$  m and a depth of 0.07 m are small too. This restricts the generalizability of results. So that scaling to field conditions is necessary. This is the next step of this research.

## **CONCLUSION**

This innovative study, using NH as an effective solution for controlling soil erosion on embankments of forest roads and reducing runoff, achieved promising results. The findings revealed that the use of NH, especially when combined with grass and natural materials such as straw and sawdust, led to a significant reduction in runoff and sediment compared to bare soil. In contrast, the control treatment, which involved no intervention, recorded the highest levels of runoff and sediment, indicating the lack of effective erosion control in such areas. The results also showed that as slope was elevated, runoff and sediment significantly increased. At higher slopes (30%), runoff and sediment were much greater than at lower slopes (10%), indicating that slope steepness acts as a key factor in accelerating soil erosion and increasing runoff volume. However, the NH treatments were still able to significantly reduce runoff and sediment, even on steeper slopes. Using NH, especially under heavy rainfall

conditions and on steep slopes, increased soil cohesion and improved its permeability. Given that this study was conducted in small plots, with each treatment having a unique effect, it is recommended that future research be conducted in larger plots and over a longer period in natural settings to obtain more practical results. Overall, the results of this study highlight the significant impact of slope as a variable, emphasizing the necessity of implementing soil conservation practices on sloped terrains to prevent severe erosion. This study demonstrates that NH can be an effective and sustainable solution for soil and water conservation projects. The findings can contribute to the development and improvement of sustainable natural resource management and offer new approaches for reducing soil erosion and preserving soil and water quality. Given the positive effect of NH on controlling runoff and sediment, it is recommended that this technology be more widely applied in areas with steep slopes and harsh environmental conditions. In conclusion, the results clearly show that NH, especially when combined with grass, is an efficient and innovative option for reducing runoff and sediment and can be used as an effective conservation solution in natural resource management projects.

### Conflict of interest

There is not any conflict of interest.

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