



# Effects of Rainwater Harvesting and Soil Amendments on Dryland Rehabilitation (Case Study: North Khorasan, Jajarm)

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## ABSTRACT

**Aims:** Improving soil properties and supplying water in rangelands are critical in these areas. For this reason, rainwater harvesting (RWH) systems are commonly used to enhance water availability. Although RWH systems and soil amendments are recognized as approaches for improving soil conditions and water availability, the combined effectiveness of these measures in environments affected by industrial activities and constrained by limited moisture is not yet well understood. This study aimed to evaluate the individual and interactive effects of three RWH methods and five soil amendment types on the initial establishment of two drought-tolerant native species, *Nitraria schoberi* and *Seidlitzia rosmarinus*. The study area is located near bauxite mines in the northern part of Jajarm County, Khorasan Province, Iran. **Materials & Methods:** The study investigated the effects of three RWH methods (contour furrow, pitting, and crescent-shaped catchments) as well as soil amendment treatments (acrylic nanoclay particles, mycorrhizal fungi (*Glomus intraradices*, *G. mosseae*, and *Glomus fasciculatum*), wheat straw mulch, and zeolite) on improving the establishment of two native plant species, *N. schoberi* and *S. rosmarinus*, which are indigenous to the study area. For this purpose, at the end of the first growing season, establishment percentage (%), height (cm), diameter (cm), and canopy cover (cm<sup>2</sup>) were measured and analyzed. The experiment was conducted in a Completely Randomized Design with 13 replications.

**Findings:** Contour furrow gave the highest establishment for both species (~91% for *N. schoberi*, ~70% for *S. rosmarinus*), while crescent and pitting methods gave lower rates. For *N. schoberi*, RWH methods significantly affected growth traits, but soil amendments had no significant effect. For *S. rosmarinus*, both RWH and amendments (especially mycorrhiza and zeolite) significantly improved height and crown diameter. Overall, for *N. schoberi*, RWH methods (especially contour furrow) are the determining factor, and soil amendment treatments provide no additional benefit; however, for *S. rosmarinus*, both RWH methods and some amendments (mycorrhiza and zeolite) significantly improve plant growth.

**Conclusion:** Contour furrow is the most effective RWH system due to uniform runoff and infiltration. Combining RWH with suitable amendments can enhance growth of rangeland species in arid industrial areas, though long-term monitoring is recommended.

**Keywords:** Contour Furrow; *G. fasciculatum*; *N. schoberi* (L.); Rangeland Rehabilitation; *S. rosmarinus* (Bunge ex Boiss.); Zeolite.

## CITATION LINKS

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## Introduction

Arid and semi-arid regions, which cover more than 40% of the Earth's land surface, have historically faced widespread water scarcity [1]. Moisture deficiency is known as the most important factor limiting forage production and vegetation establishment in arid and semi-arid regions [2]. These regions, which cover a large part of Iran, are considered sensitive and fragile ecosystems due to low precipitation of 100-150 mm across different areas, high spatio-temporal variability in precipitation, high evapotranspiration rates, and soils with low water-holding capacity [3]. In these ecosystems, limited water availability is a major constraint on plant growth, making seedling establishment and long-term vegetation survival a serious challenge. A large part of Iran's rangelands is located in arid and semi-arid climates. It plays an important role in preserving biodiversity, controlling soil erosion, providing livestock feed, and maintaining ecosystem stability [2]. Numerous studies conducted in arid and semi-arid environments indicate that rainfall deficiency and recurrent drought events markedly reduce plant productivity, underscoring the need for water-conserving technologies [4,5]. In many of these rangelands, existing natural conditions have been exacerbated by overexploitation and increasing environmental pressures, leading to the destruction of vegetation and disruption of the ecological balance in these fragile ecosystems [6]. In other words, in these areas, apart from natural factors that contribute to the high sensitivity and fragility of ecosystems, human activities and improper exploitation of rangelands also put additional pressure on them and accelerate land degradation.

Among these activities, mining, widely recognized as one of the most significant

economic activities in arid and semi-arid regions, can, if not properly managed, exert progressively greater pressure on the ecosystem and intensify land degradation. Although mining is economically important, mineral processing and quarrying activities can produce industrial dust, especially in the vicinity of other industrial pollutants, which can have more destructive effects on surrounding ecosystems than natural dust. In addition, abandoning mines after extraction without implementing vegetation restoration programs results in land degradation, heavy metal contamination, and increased wind and water erosion in surrounding areas [7]. Improper exploitation of rangelands has led to the loss of vegetation and disruption of their ecological balance. In some of these rangelands, this balance has not yet been restored due to land degradation, microclimatic changes, and various environmental stresses, making it difficult to restore ecosystem balance. Therefore, using native plant species and facilitating their establishment are key requirements for restoring these sensitive ecosystems [8, 9]. Given the high fragility of these ecosystems, identifying suitable species and understanding their establishment processes (especially in the early stages of growth) plays an important role in the success of restoration projects. In addition, an unfavorable precipitation regime, high evapotranspiration rates, and water-limited soil conditions have contributed to a marked decline in soil moisture, which, in turn, facilitates vegetation loss and increases the vulnerability of these areas to both water- and wind-driven erosion [10]. The existence of these conditions has prompted researchers to use solutions such as rainwater-harvesting methods [11-15] and

soil amendment treatments <sup>[16-20]</sup> to increase productivity and create favorable conditions for vegetation establishment in harsh regions <sup>[21,22]</sup>. When applied simultaneously, rainwater harvesting (RWH) systems and soil amendments can reinforce soil stability, improve fertility, and substantially increase plant survival and growth, particularly in nutrient-poor and degraded lands <sup>[23]</sup>.

In arid and semi-arid regions, effective management methods, such as optimal irrigation systems and mulching, are particularly important for maintaining soil moisture by enhancing rainfall storage and soil surface cover <sup>[24,25]</sup>. Methods such as constructing catchment systems (e.g., pitting, furrow contours, and crescent-shaped catchments <sup>[26]</sup>), applying biological or mineral mulches, and physical soil amendments <sup>[27]</sup> can increase moisture retention, reduce evaporation, and improve the sustainability of natural and agricultural systems <sup>[28,29]</sup>. Evidence shows that these measures not only increase water-holding capacity but also play an important role in preventing soil erosion and reducing nutrient leaching <sup>[24,30]</sup>. A report by the Food and Agriculture Organization of the United Nations shows that the use of such methods can increase soil moisture by about 30% and improve plant performance under water stress conditions <sup>[29]</sup>.

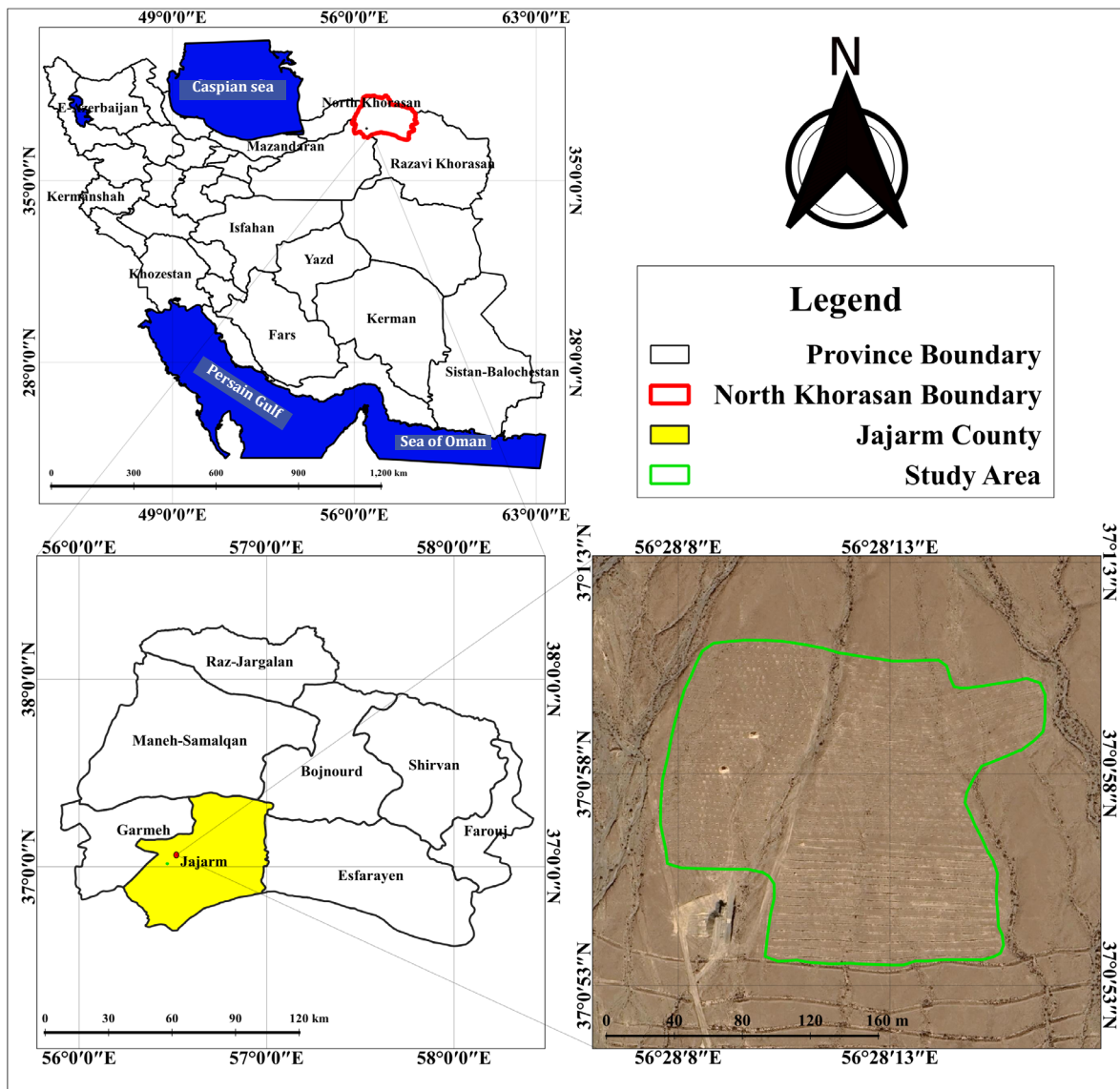
In recent years, many studies have investigated the effects of rainwater-harvesting methods and soil amendment treatments on vegetation establishment in arid and semi-arid regions. Their results show that the use of mechanical measures such as terracing, bank construction, and water storage ponds can improve soil and hydrology conditions, and promote plant growth <sup>[28,31,32]</sup>. However, the choice and application of these methods must be site-specific, cost-

effective, and economically justifiable <sup>[14]</sup>.

However, the effectiveness of mechanical methods may diminish over time; it is often suggested that they be combined with bioengineering and the application of soil amendments <sup>[31]</sup>. Treatments such as organic matter, biochar, mycorrhizal fungi, and mineral amendments have also been studied independently, and results have shown that these treatments can increase soil water-holding capacity and reduce drought stress <sup>[33,34]</sup>. In a study by Azimi et al. (2017) investigating the potential for improving the early establishment and growth of the rangeland species *Agropyron elongatum* in heavy metal-contaminated mining lands of the East Mashhad Cement Factory, it was found that the application of zeolite and mycorrhiza (*G. intraradices*) significantly increased seedling establishment percentage (46% and 65%, respectively), shoot dry weight (54% and 73%), total dry weight (56% and 68%), and plant height (48% and 54%) compared to the control treatment. Furthermore, these treatments significantly increased root dry weight and effectively improved plant tolerance to the unfavorable conditions of contaminated soils and harsh regions <sup>[35]</sup>.

In addition, some studies have shown that combining mechanical and biological methods can significantly improve the growth and establishment of plant species in arid ecosystems <sup>[14,36,37]</sup>.

In this regard, Mendez-Argueu et al. (2018) observed that adding clinoptilolite zeolite to soil increased water holding capacity by 260% <sup>[40]</sup>. Cao et al. (2024) also showed that polyvinyl alcohol, when used as a polymer binder, improved soil water stability and increased germination and plant growth rates <sup>[39]</sup>. Debebe et al. (2025) reported that in rainfed farmlands



**Figure 1)** Location of the Study area within Iran’s political boundaries.

of the African Sahara, combining RWH systems with organic soil amendments, such as poultry manure biochar, in agroforestry systems increased soil pH by 19.4% and improved maize yield by 74%. Also, the simultaneous application of rainwater-harvesting and soil-amendment techniques in semi-arid areas has been shown to increase crop yields significantly. In their field experiment, the biochar treatment (BWAFS) also significantly increased soil organic matter (from 1.21% to 2.26%) and available phosphorus (by 78.1%) compared to the control. Other amendments,

such as fresh poultry manure and wood ash, showed positive but lower effects. The control treatment (agroforestry alone without RWH or amendments) consistently yielded the poorest results. These findings confirm that integrating RWH with appropriate organic amendments can simultaneously address water scarcity and soil fertility degradation in dryland agroecosystems [23–38]. Given the increasing demand for sustainable land restoration and efficient resource use, evaluating combined and field-scale applications of RWH and soil amendment

techniques becomes particularly important. However, very few studies have systematically investigated the simultaneous effects of different RWH methods (e.g., contour furrow, pitting, crescent-shaped catchment) combined with various soil amendment treatments (e.g., acrylic clay nanoparticles, mycorrhizal fungi, straw mulch, zeolite) on the establishment and growth performance of native rangeland species, especially in arid areas adjacent to mining zones [41]. This research gap is even more pronounced for species such as *N. schoberi* and *S. rosmarinus* under real conditions. Therefore, the present study adopts an integrated experimental approach to assess the simultaneous effects of different RWH systems and soil amendment treatments on the establishment and growth performance of *N. schoberi* and *S. rosmarinus*. The outcomes of this research are expected to provide practical insights for improving rangeland rehabilitation strategies and to contribute to the development of sustainable land management practices in arid environments.

## Materials & Methods

### Study Area

The study was conducted in the desert and steppe regions of southern North Khorasan Province, located north of Jajarm County and on the plains south of the Bahar mountain range. The elevation of the site ranges from 1,100 to 1,200 m above mean sea level. Moreover, the prevailing slope of the area is 7-10 %. The soil texture of the area is loamy-sandy; its pH is 8.8-8.2; and its salinity is 3.2-4.8 dS.m<sup>-1</sup>. Geologically, the study area lies within the Qt1 Formation. This formation is mainly composed of high-level pediment-fan and valley-terrace deposits.

According to the De Martonne climate

classification, the region has a desert climate, with an mean annual precipitation of 100-150 mm. A spatial analysis of seasonal precipitation in North Khorasan Province indicates that the highest rainfall occurs in winter, predominantly in the northern and central regions, with decreasing amounts toward the southern areas, which correspond to the study area. Winter precipitation accounts for approximately 39% of the annual total, while summer rainfall is minimal and nearly negligible within the region [42]. The limited vegetation cover, soil-limited conditions, and gentle slope increase rainfall erosivity, leading to surface, rill, and temporary gully erosion. The rangelands are used by semi-nomadic pastoralists, whose livestock composition is approximately 10% goats, 80% sheep, and 10% other animals. Grazing typically begins in early to mid-April and continues until late June. Due to early grazing and high stocking rates, the area is subjected to intensive grazing pressure. The dominant rangeland vegetation type consists mainly of shrub species, including *Artemisia sieberi*, *Salsola orientalis*, and *Salsola arbusculiformis* [3].

### Project Implementation Steps

This study was conducted as a factorial experiment based on a completely randomized design (CRD) with 13 replications. The experiment was conducted at the research site located in Rangelands near the Alumina mines of Jajarm in north Khorasan, characterized by a semi-arid climate, a mean annual rainfall of 150 mm, and sandy-loam soil with a slope of approximately 7-10%. A total of 234 plants of the two cultivated species (*N. schoberi* and *S. rosmarinus*) were established in the study area. Before planting, composite soil samples were collected from the top 0-30 cm layer for analysis of texture, pH, EC, and organic matter. Seedlings of the selected species were

produced in the greenhouse of Gorgan University of Agricultural Sciences and Natural Resources (GUASNR) under controlled conditions (mean temperature  $25 \pm 2$  °C, relative humidity 60–70%). Seedlings were grown for six months until reaching a height of approximately 15–30 cm before field transplantation. After initial growth, the seedlings were transplanted to the study area in April 2024. The species were planted under direct supervision in pre-prepared growing media. All seedlings were obtained from this single, uniform nursery source to minimize initial variation and reduce the chance of inherent superiority of any seedling at planting. They were then systematically allocated to the treatment plots according to the pre-established layout of RWH systems and soil amendments. The experiment included three RWH systems (crescent-shaped catchment, pitting, and contour furrow) combined with five soil treatments involving: acrylic nanoclay particles, Mycorrhizal fungi, wheat straw mulch, zeolite, and a control (no treatment). The irrigation regime was designed to gradually reduce the plants' dependence on supplemental irrigation, ultimately facilitating their adaptation and establishment in the field. To this end, the first irrigation was carried out simultaneously with the establishment of the species in April 2024. Thereafter, during the first establishment year, 10 irrigations with approximately 20 L of water per seedling were applied. This pattern helps plants develop proper, adaptive roots to the new conditions they encounter. Irrigation amounts will be reduced in subsequent establishment years. A detailed description of the experiments is provided below.

### **Construction of Rainwater Harvesting (RWH) Systems**

To establish the crescent-shaped catchments within the study area, factors such as runoff volume, rainfall intensity, slope gradient, existing vegetation cover, and soil texture were considered. The openings of the crescent-shaped catchments were directed upslope to capture incoming runoff. These crescent-shaped catchments were constructed before the spring rains using machinery and labor, with dimensions of 3 m in diameter, 40 cm in depth, 150 cm radius, 20 cm spillway depth, and an approximate storage volume of  $1 \text{ m}^3$ . Subsequently, each target species was planted within the crescent-shaped catchments after the desired treatments were applied. For the contour furrow system, shallow furrows 20 cm deep were excavated along the contour lines. The distance between these furrows was set at 100 cm, and the target plant species were planted along the created furrows at intervals of 500 cm from each other. In the pitting method, pits measuring  $40 \times 40$  cm (40 cm deep) were dug in a strip pattern, and the selected plant species were established in these pits [43–44].

### **Application of Soil Amendment Treatments**

**Nanoparticles:** The most important characteristic of nanoclay is its ability to absorb and gradually release nutrients and water. This property reduces fertilizer consumption and decreases pest incidence in plants [25]. To this end, nanoparticle treatment was applied at two different levels: 1% and 3% acrylic resin–clay nanoparticles [45]. After planting and establishment, the mixture was prepared as a slurry and then poured at the base of the plant.

**Mycorrhizal Fungi:** The symbiosis of various plant species with mycorrhizal fungi has many positive effects on plant quantity and

quality, and also reduces the adverse effects of drought stress, nutrient deficiency, and salinity, while improving plant growth and increasing plant resistance after stress [27]. To apply this treatment, three different species of mycorrhizal fungi were used: *G. intraradices*, *G. mosseae*, and *G. fasciculatum*. The required amount of mycorrhizal treatment was 50 g of each fungal species per plant, which was added to the soil, and irrigation was carried out immediately after planting.

**Straw Mulch:** Organic mulches, including plant twigs, straw, and stubble, help retain soil moisture, reduce bulk density, and decrease soil surface compaction. As a result, by reducing evaporation and strengthening soil aggregates, they increase water holding capacity [36]. This treatment consisted of wheat straw stubble spread on the soil surface around the plant species to a thickness of 3 cm. It should be noted that before this operation, the soil surface was slightly moistened with water to prevent the straw from scattering.

**Zeolite:** Zeolite acts as an effective adsorbent for cations and anions, absorbing up to 70% of its weight in water without altering soil conditions, thereby contributing to soil moisture retention [46]. To apply this treatment, two levels of zeolite were used; 10% and 20% of the pit weight (equivalent to 300 and 600 g) per plant. After digging the pits, the different treatment levels were applied to the soil, and irrigation was then performed.

Clay nanoparticles were obtained from Novaplast Company (Semnan, Iran), which, due to their unique structure, have broad applications in improving the physico-chemical properties of soil. Zist Fanavare Touran Company supplied mycorrhizal fungi. Furthermore, the zeolite used in this study was procured from Niakan Sangsar Company.



(A)



(B)



(C)



(D)

**Figure 2)** Bed Preparation and construction of rainwater harvesting systems in the study area (A); contour furrows (B); pitting (C), and crescent-shaped catchment (D).

**Measurement and Data Analysis**

The characteristics of all 234 established plants (including survival rate (establishment), canopy cover, plant height, major crown diameter, and small minor crown diameter, which represent the primary indicators of plant growth and development) were measured during the first growing season after establishment (late summer 2024) using a graduated vertical ruler (With 1 cm measurement error). Canopy cover was calculated based on these measurements [47-48]. Canopy cover is the product of minor crown diameter multiplied by major crown diameter. The establishment percentage was determined by counting the number of surviving seedlings. Data analysis was performed using Minitab software (version 16.0). First, the data’s normality was tested using the Kolmogorov–Smirnov test. Subsequently, statistical analyses, including analysis of variance (ANOVA) and Tukey’s post hoc test, were conducted separately for each species to evaluate the effects on plant height, major crown diameter, minor crown diameter, and canopy cover.

**Table 1)** Establishment percentage of *N. schoberi* and *S. rosmarinus*.

Species	Rainwater Harvesting	Establishment (%)	Total Establishment (%)
<i>N. schoberi</i>	Contour Furrow	90.85	73.50
	Pitting	66.63	
	Crescent-Shaped Catchment	63.20	
<i>S. rosmarinus</i>	Contour Furrow	69.91	64.59
	Pitting	55.53	
	Crescent-Shaped Catchment	68.34	



(A)



(B)

**Figure 3)** Establishment of *N. schoberi* in the study area (A), and Establishment of *S. rosmarinus* in the study area (B).

**Findings**

The establishment percentage was assessed across different water-harvesting methods in the study area (Table 1). The results showed that for *N. schoberi*, the contour furrow method achieved the highest establishment rate (90.85%), while the crescent-shaped catchment showed the lowest (63.2%). Similarly, for *S. rosmarinus*, the contour

furrow method resulted in the highest establishment rate (69.91%), whereas the pitting method had the lowest (55.53%). The results of the analysis of variance for *N. schoberi* (Table 2) showed significant differences among the three water-harvesting methods (contour furrow, pitting, and crescent-shaped catchment) in plant height and major and minor crown diameters. However, no significant differences were observed among the applied soil amendment treatments for any of the studied traits.

The analysis of variance for *S. rosmarinus* (Table 3) indicated significant differences among the three rainwater harvesting methods (contour furrow, pitting, and crescent-shaped catchment) for the traits

of major crown diameter and canopy cover. Moreover, among the applied soil amendment treatments, significant differences were observed in plant height and the major and minor crown diameters.

The comparison of mean values and grouping of the studied factors for *N. schoberi* (Figure 4) indicated that plant height formed a single statistical group, with the highest mean observed in the *G. fasciculatum* treatment and the lowest in the 300 g Zeolite treatment. The greatest mean plant height was recorded in the contour furrow planting system. The major crown diameter also formed a single group, showing the highest mean in the control treatment and the lowest in the 3% nano-clay treatment, while the highest value was observed in the pitting system. Similarly,

**Table 2)** Analysis of variance (ANOVA) for the effect of rainwater harvesting methods and corrective treatments on *N. schoberi*.

Source of Variation	Mean of Squares (MS)				
	df	Height	Major Crown Diameter	Minor Crown Diameter	Canopy Cover
Rainwater Harvesting	2	926.63**	77.75*	30.064**	1905 <sup>ns</sup>
Corrective Treatment	8	102.44 <sup>ns</sup>	18.99 <sup>ns</sup>	2.771 <sup>ns</sup>	1370 <sup>ns</sup>
RWH×CT	16	141.93**	37.46*	11.467**	2465*
Error	243	61.73	18.99	3.455	1399
Total	269				

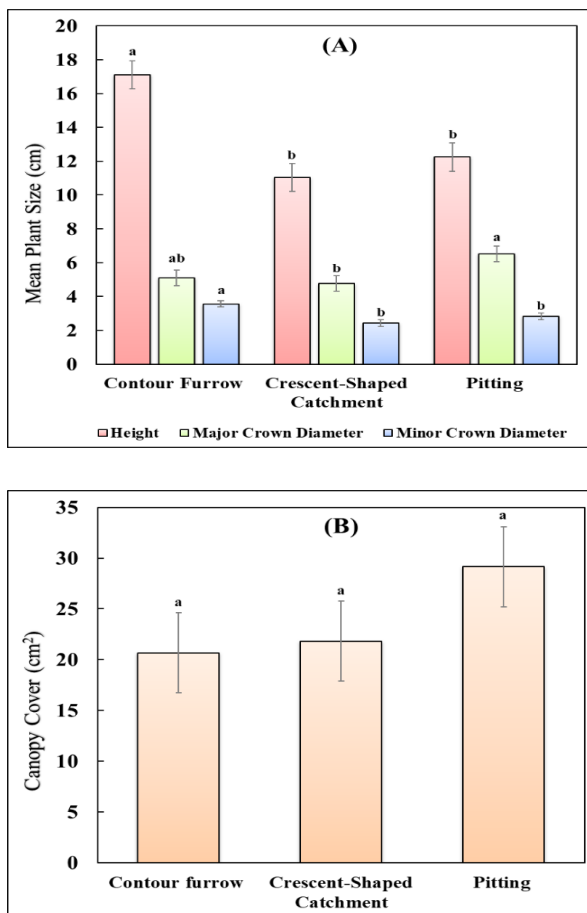
\*\* : Highly significant, \* : Significant, <sup>ns</sup> : Not significant

**Table 3)** Analysis of variance (ANOVA) for the effect of rainwater harvesting methods and corrective treatments on *S. rosmarinus*.

Source of Variation	Mean of Squares (MS)				
	df	Height	Major Crown Diameter	Minor Crown Diameter	Canopy Cover
Rainwater Harvesting	2	146.48 <sup>ns</sup>	136.12*	2.53 <sup>ns</sup>	19232*
Corrective Treatment	8	259.31**	123.39**	25.11*	8417 <sup>ns</sup>
RWH ×CT	16	277.77**	79.43**	37.60**	7197 <sup>ns</sup>
Error	323	69.30	36.84	12.11	5045
Total	349				

\*\* : Highly significant, \* : Significant, <sup>ns</sup> : Not significant

the minor crown diameter was distributed into 3 groups, with the highest mean in the control treatment, the lowest in the 300 g Zeolite treatment, and the contour furrow system having the highest mean. For canopy cover, all treatments formed a single statistical group, with the highest mean observed in the control treatment and the lowest in the 300 g Zeolite treatment; the largest canopy cover was recorded in the pitting planting system.



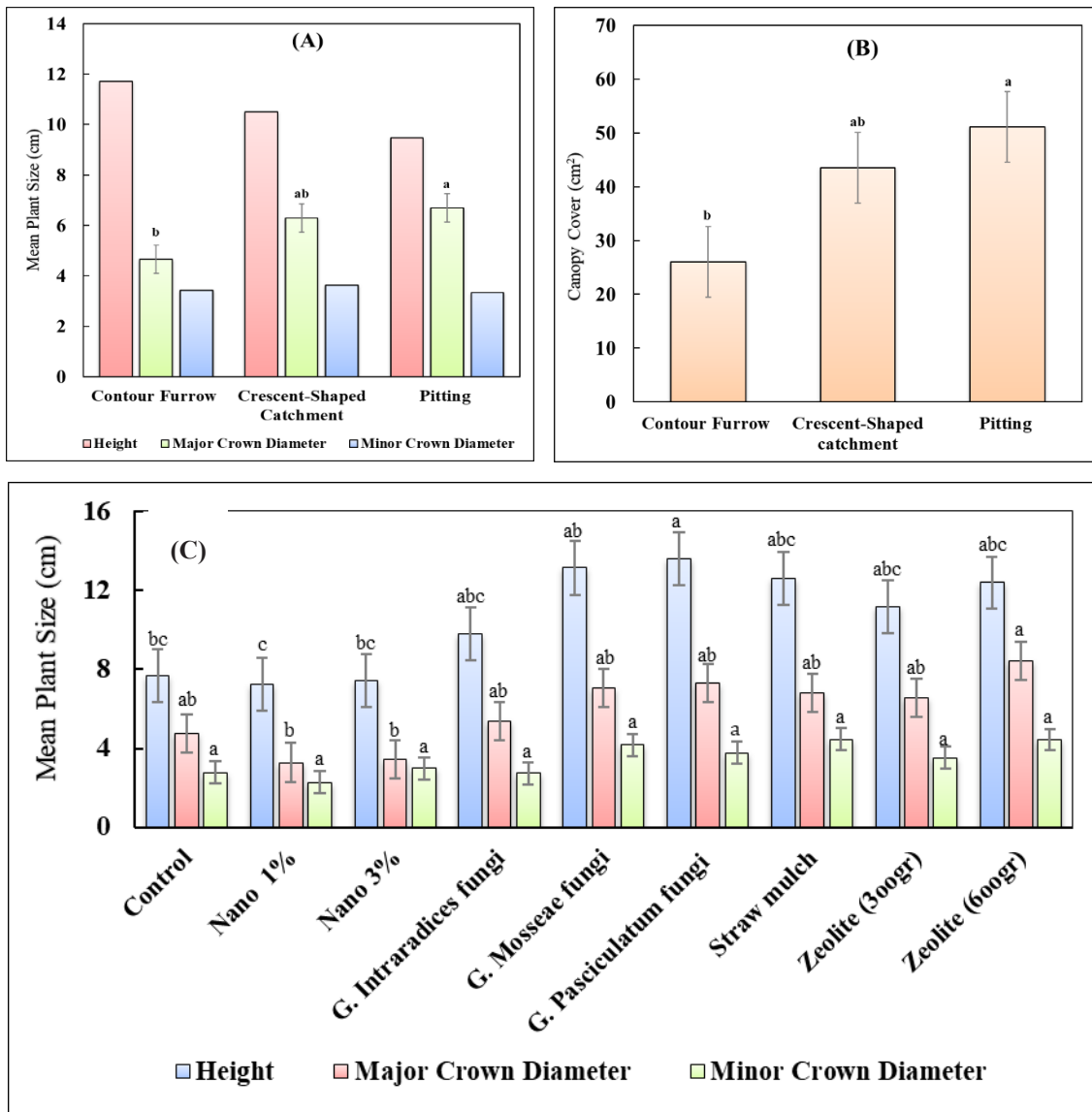
**Figure 4)** Comparison of planting beds (A) and canopy cover (B) of *N. schoberi* species under different rainwater harvesting methods (contour furrow, pitting, and crescent-shaped catchment).

The comparison of mean values and grouping of the studied traits for *S. rosmarinus* (Figure 5) showed that plant height was divided into five statistical groups, with the highest mean observed in the *G. fasciculatum* treatment and the lowest in the 1% nano-clay treatment.

The greatest mean height was recorded in the contour furrow planting system. The major crown diameter was classified into three groups, with the highest mean observed in the 600 g Zeolite treatment and the lowest in the 1% nano-clay treatment; the highest value was recorded in the pitting system. The minor crown diameter formed a single statistical group, with the highest means observed in the 600 g Zeolite and straw mulch treatments, and the lowest in the 1% nano-clay treatment; the largest mean value was recorded in the crescent-shaped catchment system. For canopy cover, all treatments were grouped, with the highest mean recorded in the 600 g Zeolite treatment and the lowest in the 1% nano-clay treatment; the largest canopy cover was observed in the pitting planting system.

## Discussion

The results of this study showed that different rainwater harvesting (RWH) techniques had various effects on the establishment and growth of the studied species in the experimental site. For *N. schoberi*, the contour furrow method exhibited the highest establishment rate (90.85%) compared with the pitting and crescent-shaped catchment methods. Similarly, for *S. rosmarinus*, the contour furrow method resulted in the highest establishment rate (69.91%), while the pitting showed the lowest (55.53%). This superiority may be attributed to the more uniform distribution of runoff, enhanced water infiltration, and improved soil moisture retention in the contour furrow system. The higher establishment rates observed in contour furrows are consistent with mechanisms reported in the literature (e.g., improved infiltration and moisture retention). Nevertheless, direct



**Figure 5)** Comparison of planting beds (A) and canopy cover (B) for *S. rosmarinus* species under different rainwater harvesting methods (contour furrow, pitting, and crescent-shaped catchment) and soil amendment treatments (C).

measurements of soil moisture and runoff distribution are needed in future studies to confirm these proposed mechanisms. Findings of this study indicate that among different RWH methods, level furrows exhibit the highest efficiency in establishing *N. schoberi* and *S. rosmarinus*. This superiority can be explained by mechanisms previously reported in the literature. Specifically, Debebe et al. (2025) demonstrated that integrating RWH systems

with organic amendments, such as biochar, significantly increases soil pH, organic matter, and available phosphorus, thereby improving crop yields in rainfed lands [23]. Comparing these results with the present conditions suggests that level furrows, by creating a greater capacity for moisture storage, provide an environment similar to that of biochar treatment, an environment where increased moisture enhances microbial activity, accelerates organic matter

decomposition, and increases nutrient availability. These conditions are directly aligned with the higher establishment rate observed with this method. In contrast, the pit excavation method, which showed the lowest establishment rate, likely failed to adequately activate the essential biological and chemical processes due to insufficient stored moisture.

Other studies also indirectly support the superiority of level furrows. For instance, Cao et al. (2024) reported that using polyvinyl alcohol as a polymeric binder improves soil aggregate stability and enhances seed germination and plant growth<sup>[39]</sup>. The performance of level furrows in reducing surface runoff and increasing soil stability can be considered analogous to the stabilizing effect of polymers. Furthermore, results from Mendez-Argueu et al. (2018) showed that adding clinoptilolite zeolite increased soil water holding capacity by up to 260%<sup>[40]</sup>. Although no physical or organic soil amendments were used in the present study, it can be predicted that combining level furrows with materials such as biochar or zeolite could enhance the performance of this method beyond current values (90.85% and 69.91% for the two species, respectively).

Given the totality of the evidence, this study's results emphasize that the effectiveness of RWH methods is not limited to their geometric configuration or runoff direction; rather, the interaction among stored moisture, microbial activity, nutrient dynamics, and soil physical stability is decisive. Therefore, to increase the success of plant establishment in arid regions, adopting an integrated approach that combines appropriate rainwater-harvesting methods with organic and inorganic amendments can

yield substantially greater effectiveness than using any of these strategies individually. It should be noted that supplemental irrigation was applied during the establishment phase: 10 irrigation events in the first year, followed by a gradual reduction in subsequent years to encourage root development and reduce dependency on artificial water supply. This irrigation regime was applied uniformly across all treatments. Therefore, the observed differences between RWH methods and soil amendment treatments are primarily attributable to the tested factors, not to irrigation. However, the initial irrigation may have facilitated early survival, particularly in treatments with lower water retention capacity (e.g., pitting without amendments).

The soil amendment treatments produced different responses between the two species. In *N. schoberi*, none of the applied amendments had a statistically significant effect on the measured growth traits. However, in *S. rosmarinus*, soil amendments significantly affected plant height and both major and minor crown diameters. Ecological traits can explain this species-specific response: *N. schoberi* is a deep-rooted, stress-tolerant shrub that accesses water and nutrients from deeper soil layers, making it less dependent on surface amendments in the short term. In contrast, *S. rosmarinus* has a shallower root system and a higher relative growth rate, allowing it to respond more rapidly to surface soil improvements. These findings suggest that longer-term observations may be necessary to detect potential cumulative effects of soil amendments in *N. schoberi*. Similarly, Dehdari et al. reported that zeolite application may not have a significant short-term impact on vegetative characteristics but can improve

soil structure and water-holding capacity over time <sup>[49]</sup>.

The findings indicate that the combined application of rainwater-harvesting systems and soil amendments enhanced the establishment and growth performance of *S. rosmarinus*. For *N. schoberi*, although soil amendments alone showed no significant short-term effects, the contour furrow system (as a RWH technique) significantly improved its establishment rate (90.85%) compared to pitting and crescent-shaped methods, independent of amendment effects. The contour furrow system outperformed other water-harvesting methods for both species, likely due to its ability to efficiently guide surface runoff, promote water infiltration, and maintain soil moisture in the root zone. These results are consistent with those of Habibzadeh & Noroozi and Bahmadi & Shahriari.<sup>[14,15]</sup>

A significant interaction was also observed between soil amendment treatments and RWH systems, particularly in *S. rosmarinus*. This suggests that certain amendments may exert notable effects only under specific planting systems or in combination with particular water-harvesting methods. In our study, the combination of *G. mosseae* with contour furrow and pitting methods had highly significant effects on vegetative traits (plant height and major and minor crown diameters). It produced the highest mean values among all treatments for *S. rosmarinus*. Similar interactive effects were reported by Debebe et al. (2025) and Mak-Mensah et al. (2022), who indicated that combining organic or biological soil amendments (e.g., biochar, mycorrhizal fungi, zeolite) with water-harvesting structures improves soil physical properties, nutrient uptake, and plant growth <sup>[23, 38]</sup>.

## Conclusion

This study evaluated the effects of different rainwater harvesting (RWH) techniques (contour furrow, pitting, crescent-shaped catchment) and soil amendment treatments (including mycorrhizal fungi (*G. intraradices*, *G. mosseae*, and *G. fasciculatum*), wheat straw mulch, and zeolite) on the establishment and growth of *N. schoberi* and *S. rosmarinus* under desert conditions at a single experimental site in Arid and semi-arid rangelands adjacent to Jarjarm alumina mines.

The findings demonstrate that the contour furrow technique performs most effectively in improving establishment percentage and growth of both species, mainly due to its uniform runoff distribution and enhanced water infiltration into the soil. Moreover, the distinct responses of the two species to soil treatments underscore the importance of biodiversity and the need to adopt species-oriented strategies in rangeland restoration management.

To evaluate the persistence of treatment effects, longer monitoring periods are required, as the cumulative benefits of certain treatments (e.g., zeolite) may emerge over time. The use of clay-acrylic resin nanocomposites as a soil conditioner, combined with a factorial experimental design and thirteen replications, represents a methodological innovation in dryland restoration research.

Several recommendations are proposed for future studies: first, replicating this experiment across multiple sites with varying soil and climatic conditions; second, conducting long-term monitoring (at least three years) to detect delayed responses, particularly for deep-rooted species such as *N. schoberi*; and third, performing economic evaluations to assess the cost-effectiveness

of the proposed techniques.

From a management perspective, the contour furrow method is recommended for restoration projects in similar desert environments to improve plant establishment. Among all tested combinations, contour furrow + *G. fasciculatum* showed the strongest effects on vegetative traits (plant height and stem diameter) for *S. rosmarinus*, followed by contour furrow + *G. mosseae* and pitting + *G. fasciculatum*. For more sensitive species such as *S. rosmarinus*, combining contour furrow or pitting with biological amendments (e.g., *G. mosseae*) can enhance early growth. Overall, species-oriented strategies based on ecological traits (e.g., root depth) should guide the selection of appropriate treatments.

In summary, although the integration of mechanical and biological approaches in this study represents a promising step towards the sustainable restoration of arid ecosystems, the results should be interpreted as site-specific until further validation across multiple sites.

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