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## **SAINFOIN (*ONOBRYCHIS ADANS.*) RESPONSE TO MINERAL FERTILIZERS THROUGH PRODUCTIVITY AND QUALITY TRAITS UNDER GRAY-BROWN SOIL CONDITIONS**

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### **SUMMARY**

Sainfoin (*Onobrychis Adans.*) is a valuable perennial legume widely cultivated in mountainous areas; however, its minimal productivity often results from degraded mountain gray-brown soils with low fertility and poor structure. The relevant study aimed to evaluate the effect of mineral fertilizer application on root development, productivity, and forage quality of sainfoin for three consecutive years under mountain gray-brown soil conditions. Field experiments had different mineral fertilizer compositions laid out in moderately and severely eroded mountain gray-brown soils for three years to evaluate their impact on the root biomass and morphology, plant growth, yield, and nutritional quality. The results showed balanced mineral fertilization significantly improved the root system, enhancing nutrient uptake and plant stability. Fertilizer application also stimulated the plant's vegetative growth and development with increased green and dry matter yields compared with the unfertilized control. Forage quality parameters, including crude protein content and fiber composition, also displayed considerable improvement under optimized fertilizer regimes. On average, moderate and well-balanced fertilizer doses provided the best combination of enhanced root development, higher yield, and improved forage quality. Mineral fertilizer application significantly enhanced the sainfoin productivity and feed value and offered practical recommendations for sustainable pasture management in degraded and eroded mountain gray-brown soils.

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**Keywords:** Sainfoin (*Onobrychis* Adans.), legume crops, mineral fertilizers, root development, forage quality, productivity, eroded mountain gray-brown soils, soil fertility, sustainable pasture management

**Key findings:** Balanced mineral fertilizer application significantly improved the root development, green and dry matter yields, forage quality, and crude protein content in sainfoin (*Onobrychis* Adans.) under eroded mountain gray-brown soils. Moderate fertilizer doses proved most effective, offering the best balance between productivity, forage nutritive value, and sustainable soil management.

## INTRODUCTION

Intensive moderately eroded and severely eroded decomposition processes have removed a substantial portion of fertile land in the western regions of the Republic of Azerbaijan, particularly on the northeastern slope of the Lesser Caucasus. Restoring these degraded areas and reintegrating them into productive use earnestly require various soil-rehabilitation measures. The most cost-effective and widely applicable soil-protective agrotechnical practices are the cultivation of perennial leguminous grass on lands subjected to different degrees of erosion. Perennial legumes, especially sainfoin (*Onobrychis* Adans.), exhibited the highest nutrient demands and, therefore, play a viable role in soil improvement (Shukurov *et al.*, 2025).

However, in the eroded zones of the study area, the easily assimilable nutrient contents significantly disappear and, even in some cases, are entirely absent. Under such nutrient-deficient and structurally soil-degraded conditions, the root systems of perennial leguminous species develop weakly, with limited branching, and face hindrances in penetrating deeper soil layers. Consequently, only a small amount of underground biomass accumulates in the upper soil layers. Instead of extending into deeper soil profiles, plant roots tend to concentrate in the upper soil layers to develop more intensively with increased lateral branching (Interstate standard, 2019; Sadigov, 2023).

Observations in the study area revealed the use of mineral fertilizers within the recommended dosage on moderately and severely eroded lands regulated the distribution of branching roots and rhizomes of perennial leguminous grasses within the crop

layer. This, in turn, had a positive effect on the restoration and stabilization of eroded soils. Such studies under various soil and environmental conditions disclosed that perennial leguminous grasses accumulate a significant portion of their root mass in the crop layer and reported dry root biomass (4 to 15 t/ha), equivalent to approximately 16–60 tons of organic manure. The majority of the root mass (83%–84%) gathered in the 0–10 cm layer, while around 15.5%–16.0% appeared in the 10–20 cm layer.

In previous research, V.M. Machavariani (1961) studied the washed brown forest soils in Eastern Georgia. Said study found that a mixture of poplar (*Populus nigra*), black alfalfa, and tongalotu (*Bromus*) retained 7.63, 11.38, and 12.83 t/ha, respectively, in the 0–40 cm soil layer over three years, predominantly concentrated in the 0–10 cm layer. Similarly, M.N. Zaslavski (1986) demonstrated in Moldova that perennial grasses maintained the bulk of their root mass in the sown layer of eroded soils. For example, in the first year, black alfalfa contained 4.52, 2.37, and 1.02 t/ha in the 0–10, 10–20, and 20–30 cm layers, respectively, with gradual adjustment in the subsequent years, while sainfoin (*Onobrychis* Adans.) roots showed a similar distribution pattern (Sadigov, 2018; Khalilov *et al.*, 2023; Gumbatov *et al.*, 2024).

Root systems of perennial leguminous grasses in the plow layer proved crucial for enhancing the fertility of moderately and severely eroded soils. Therefore, proper application of mineral fertilizers within recommended rates is essential; insufficient fertilization can limit soil structure restoration, reduce nutrient availability, and impair pertences of air-water permeability. Even if crop plants actively develop, suboptimal

fertilization cannot ensure the high productivity of crops (Sadigov, 2022; Mammadov *et al.*, 2025).

Different field and laboratory methods proceeded to study the research object in the northeastern part of the Lesser Caucasus, Azerbaijan. Field investigations also relied on preliminary laboratory assessments. Research boundaries' delineation used topographic maps at scales of 1:100,000 and 1:50,000. Within these boundaries, establishing field survey routes continued, with soil sections laid out along these routes and the geographic coordinates of each sampling point recorded. Fieldwork progressed, referring to the available topographic maps, ensuring systematic coverage of the study area (Mammadov *et al.*, 2025).

## MATERIALS AND METHODS

The comparative geographical method, as extensively applied, examined the variations across the research object. The natural and ecological conditions of the study area entailed characterization that included relief, climatic parameters, vegetation cover, hydrography, and geological and geomorphological structures. Soil sections bore systematic numbering, with each section being documented for its morphological features, such as thickness, granulometric composition, color, structure, hardness, and other diagnostic properties.

The field experiment took place in the mountainous regions of the northeastern slopes of the Lesser Caucasus under gray-brown soils. These soils showed characteristics of moderate to severe erosion, low organic matter content, and limited nutrient availability, which constrained plant growth and productivity. The study spanned three consecutive years (Year 1, Year 2, and Year 3) to assess the cumulative effects of mineral fertilization on sainfoin (*Onobrychis* Adans.) growth and quality traits. Sainfoin (*Onobrychis* Adans.) sowing in autumn and spring had a seed rate of 20 kg/ha. Plot size was 10 m × 5 m, arranged in a randomized complete block design with four replicates per treatment. The

experimental treatments consisted of mineral fertilizers applied at different types and rates, including nitrogen (N) at 40 kg/ha, applied in split doses—half at pre-sowing and half at the early vegetative stage. Phosphorus (P<sub>2</sub>O<sub>5</sub>) application was at 30 kg/ha, applied entirely before sowing and incorporated into the top 10 cm of soil. Potassium (K<sub>2</sub>O) treatment was at 25 kg/ha, applied at pre-sowing and mixed with the soil. Control plots received no fertilizers. Applying fertilizers was uniform across the plots using manual broadcasting, followed by light soil incorporation to ensure good contact.

All the data underwent analysis of variance (ANOVA) using SAS version 9.4. Means comparison used the least significant difference (LSD) test at  $p \leq 0.05$ . Data presentation comprised the mean ± standard deviation and the effects of fertilizer type, application rate, sowing season, and soil erosion severity, with year evaluated for both productivity and quality traits.

## RESULTS AND DISCUSSION

For soil-granulometric laboratory analysis, the collected soil samples came from distinct genetic horizons. These samples sustained analysis using modern physico-chemical and analytical methods to determine the various soil properties relevant to fertility, texture, and nutrient availability. The combined field and laboratory approaches proved a comprehensive assessment of soil properties, vegetation-root interactions, and the effect of mineral fertilizers on perennial leguminous grasses under eroded mountain gray-brown soil conditions (Khalilov *et al.*, 2023; Gumbatov *et al.*, 2024; Mammadov *et al.*, 2025; Mustafayev *et al.*, 2025; Huseynov *et al.*, 2026).

Plantation of sainfoin (*Onobrychis* Adans.) for erosion control remains poorly developed in the mountainous and foothill regions of the country, particularly on sloping terrains. In these areas, the absence of sainfoin cultivation has increased soil susceptibility to erosion, leading to an enormous loss of fertile topsoil with a significant decline in crop productivity and

quality. This situation was evident in the study area, where soil degradation has become widespread and causes significant annual losses in many crops' productivity. The limited establishment of sainfoin (*Onobrychis* Adans.) on sloping lands has exacerbated soil erosion in mountainous and foothill regions, where steep gradients and intense rainfall accelerate topsoil loss. Previous studies indicate perennial legumes, such as sainfoin, significantly improved soil structure, enhanced organic matter content, and reduced runoff and erosion when compared with annual crops or bare soils. The widespread soil degradation observed in the study area aligns with findings that the absence of deep-rooted forage crops

leads to declining soil fertility and long-term reductions in crop yield and quality (Sleugh et al., 2000; Huseynov et al., 2025).

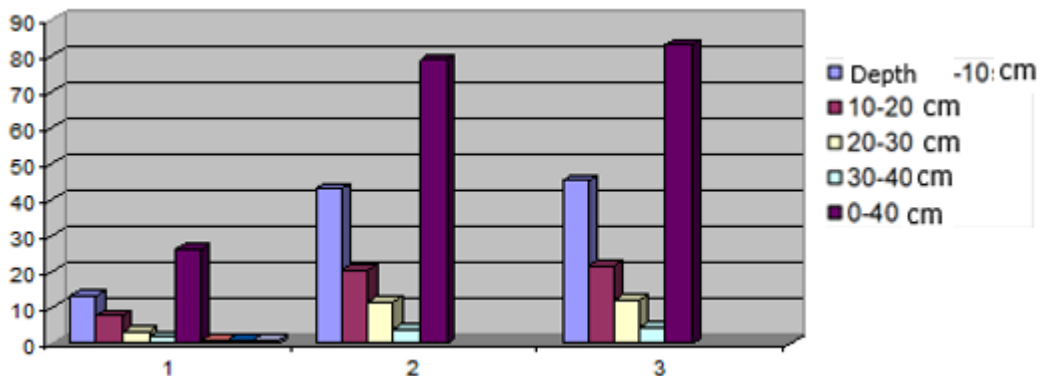
The mitigation of these losses resulted in the recommendation of the cultivation of perennial leguminous grasses, particularly sainfoin (*Onobrychis* Adans.), provided the complementation of appropriate application of mineral fertilizers. The presented study investigated the effects of mineral fertilizers applied at varying rates and combinations on the root mass of sainfoin crops in eroded mountain gray-brown soils during the 2022–2025 years of cultivation. A summary of the results of these investigations appears in Tables 1 and 2 and Figures 1, 2, 3, and 4.

**Table 1.** Effect of mineral fertilizers on the root mass of sainfoin (*Onobrychis* Adans.) in moderately eroded mountain gray-brown soils (t/ha per year).

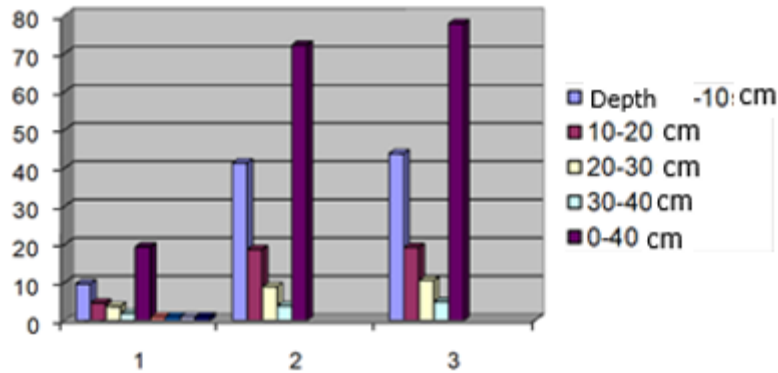
Sowing time	Experience options	Research years	Depth (cm)					
			0-10	10-20	20-30	30-40	0-40	
Autumn sowing	Fertilizer-free	I year	0.135	0.079	0.035	0.019	0.263	
		II year	0.432	0.205	0.117	0.042	0.789	
		III year	0.455	0.216	0.123	0.047	0.832	
	P <sub>45</sub> K <sub>20</sub>	I year	0.125	0.082	0.042	0.023	0.276	
		II year	0.458	0.214	0.118	0.048	0.833	
		III year	0.489	0.283	0.125	0.063	0.953	
	N <sub>30</sub> P <sub>45</sub> K <sub>20</sub>	I year	0.133	0.079	0.055	0.023	0.283	
		II year	0.465	0.228	0.121	0.055	0.864	
		III year	0.516	0.303	0.139	0.073	1.025	
	P <sub>60</sub> K <sub>30</sub>	I year	0.135	0.083	0.043	0.024	0.274	
		II year	0.479	0.215	0.115	0.054	0.857	
		III year	0.504	0.287	0.128	0.066	0.979	
	N <sub>45</sub> P <sub>60</sub> K <sub>30</sub>	I year	0.146	0.091	0.054	0.023	0.306	
		II year	0.501	0.241	0.131	0.062	0.926	
		III year	0.544	0.316	0.145	0.072	1.072	
	Spring sowing	Fertilizer-free	I year	0.097	0.046	0.037	0.019	0.193
			II year	0.414	0.187	0.089	0.038	0.722
			III year	0.438	0.192	0.105	0.049	0.779
P <sub>45</sub> K <sub>20</sub>		I year	0.098	0.059	0.037	0.021	0.209	
		II year	0.438	0.197	0.097	0.041	0.767	
		III year	0.457	0.229	0.119	0.053	0.853	
N <sub>30</sub> P <sub>45</sub> K <sub>20</sub>		I year	0.102	0.063	0.031	0.019	0.207	
		II year	0.456	0.211	0.103	0.045	0.808	
		III year	0.473	0.272	0.124	0.059	0.925	
P <sub>60</sub> K <sub>30</sub>		I year	0.106	0.064	0.031	0.022	0.219	
		II year	0.443	0.202	0.101	0.046	0.787	
		III year	0.462	0.253	0.119	0.058	0.886	
N <sub>45</sub> P <sub>60</sub> K <sub>30</sub>		I year	0.122	0.059	0.035	0.016	0.227	
		II year	0.477	0.218	0.108	0.054	0.853	
		III year	0.494	0.266	0.132	0.062	0.947	

**Table 2.** Effect of mineral fertilizers on the root mass of sainfoin (*Onobrychis Adans.*) in severely eroded mountain gray-brown soils (t/ha per year).

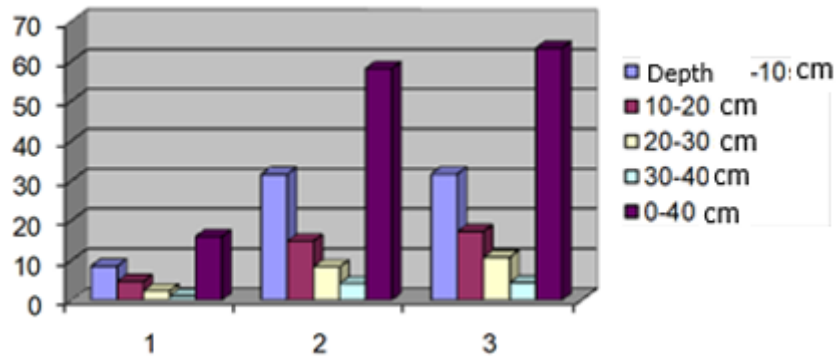
Sowing time	Experience options	Research years	Depth (cm)					
			0-10	10-20	20-30	30-40	0-40	
Autumn sowing	Fertilizer-free	I year	0.085	0.047	0.023	0.011	0.159	
		II year	0.316	0.148	0.083	0.042	0.581	
		III year	0.316	0.172	0.107	0.043	0.632	
	P <sub>45</sub> K <sub>20</sub>	I year	0.086	0.047	0.024	0.011	0.161	
		II year	0.343	0.161	0.097	0.046	0.642	
		III year	0.355	0.195	0.113	0.052	0.709	
	N <sub>30</sub> P <sub>45</sub> K <sub>20</sub>	I year	0.085	0.053	0.026	0.013	0.161	
		II year	0.358	0.163	0.104	0.054	0.673	
		III year	0.374	0.209	0.125	0.058	0.763	
	P <sub>60</sub> K <sub>30</sub>	I year	0.085	0.049	0.033	0.017	0.177	
		II year	0.355	0.171	0.099	0.041	0.672	
		III year	0.367	0.202	0.115	0.058	0.741	
	N <sub>45</sub> P <sub>60</sub> K <sub>30</sub>	I year	0.089	0.063	0.034	0.015	0.195	
		II year	0.366	0.178	0.103	0.054	0.697	
		III year	0.389	0.219	0.132	0.062	0.798	
	Spring sowing	Fertilizer-free	I year	0.061	0.034	0.017	0.008	0.121
			II year	0.299	0.132	0.079	0.035	0.541
			III year	0.304	0.141	0.099	0.042	0.592
P <sub>45</sub> K <sub>20</sub>		I year	0.067	0.034	0.018	0.008	0.122	
		II year	0.322	0.144	0.082	0.039	0.586	
		III year	0.339	0.181	0.105	0.045	0.664	
N <sub>30</sub> P <sub>45</sub> K <sub>20</sub>		I year	0.068	0.036	0.018	0.011	0.127	
		II year	0.349	0.056	0.083	0.046	0.629	
		III year	0.354	0.197	0.115	0.057	0.715	
P <sub>60</sub> K <sub>30</sub>		I year	0.068	0.038	0.021	0.006	0.129	
		II year	0.338	0.157	0.080	0.044	0.625	
		III year	0.354	0.181	0.109	0.048	0.688	
N <sub>45</sub> P <sub>60</sub> K <sub>30</sub>		I year	0.061	0.037	0.023	0.009	0.137	
		II year	0.341	0.104	0.097	0.048	0.659	
		III year	0.379	0.196	0.114	0.051	0.738	



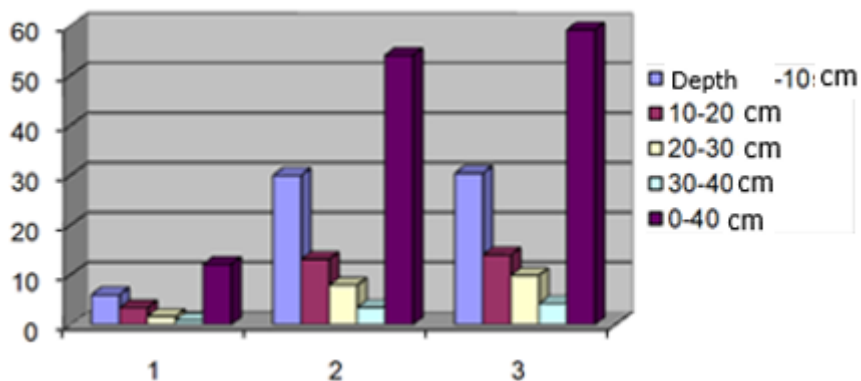
**Figure 1.** Effect of mineral fertilizers on the root mass of sainfoin (*Onobrychis Adans.*) in autumn sowing under moderately eroded mountain gray-brown soils (t/ha per year). (without fertilizer, 1-first year, 2-second year, 3-third year).



**Figure 2.** Effect of mineral fertilizers on the root mass of sainfoin (*Onobrychis* Adans.) in spring sowing under moderately eroded mountain gray-brown soils (t/ha per year). (without fertilizer, 1-first year, 2-second year, 3-third year).



**Figure 3.** Effect of mineral fertilizers on the root mass of sainfoin (*Onobrychis* Adans.) in autumn sowing under severely eroded mountain gray-brown soils (t/ha per year). (without fertilizer, 1-first year, 2-second year, 3-third year).



**Figure 4.** Effect of mineral fertilizers on the root mass of sainfoin (*Onobrychis* Adans.) in spring sowing under severely eroded mountain gray-brown soils (t/ha per year). (without fertilizer, 1-first year, 2-second year, 3-third year).

The results revealed mineral fertilizers' application has considerably influenced the root mass of sainfoin (*O. Adans.*) in both moderately and severely eroded mountain gray-brown soils, with variations based on the sowing period and year of cultivation. In moderately eroded soils, during autumn sowing, the dry root mass in the 0–40 cm soil layer ranged from 2.63 to 3.06 t/ha in the first year. It was 7.89–9.27 t/ha in the second year and 8.32–10.72 t/ha in the third year, compared with unfertilized controls. In spring sowing, the corresponding values were 1.93–2.28 t/ha (first year), 7.22–8.53 t/ha (second year), and 7.79–9.48 t/ha (third year). The observed increase in dry root mass of sainfoin under mineral fertilizer application confirms the strong role of nutrient availability in promoting root system development, particularly in eroded soils with limited fertility. Enhanced root biomass in deeper soil layers improves soil aggregation, water infiltration, and resistance to erosion, which is especially critical in mountainous environments. Similar studies have shown that perennial legumes, such as sainfoin, respond positively to fertilization, with cumulative effects becoming more pronounced in the second year and seasons of cultivations due to improved soil-root interactions and nutrient cycling (Sleugh *et al.*, 2000).

In severely eroded soils, autumn-sown sainfoin (*Onobrychis Adans.*) treated with mineral fertilizers showed an increase in dry root mass. It was 1.59–1.95 t/ha in the first year, 5.81–6.97 t/ha in the second year, and 6.32–7.98 t/ha in the third year in the 0–40 cm soil layer. Meanwhile, spring sowing resulted in increases of 1.21–1.37, 5.41–6.59, and 5.92–7.38 t/ha over the three years, respectively. The positive response of sainfoin root biomass to mineral fertilization in severely eroded soils demonstrates the crop's capacity to partially overcome nutrient limitations under degraded conditions. Greater root development in autumn sowing, particularly in the second and third years, suggests improved nutrient uptake and soil exploration, which enhances soil stabilization and reduces further erosion. These findings were consistent with earlier reports indicating that perennial legumes with well-developed root systems play a crucial role

in restoring soil structure and productivity in erosion-prone environments (Sleugh *et al.*, 2000, Amanova *et al.*, 2026).

Focusing on the 0–10 cm soil layer in moderately eroded soils, the autumn sowing increased root mass by 0.135–0.146, 0.432–0.501, and 0.455–0.544 t ha<sup>-1</sup> in the first, second, and third years, respectively. Spring sowing resulted in 0.097–0.122, 0.411–0.478, and 0.437–0.494 t ha<sup>-1</sup>, respectively. In severely eroded soils, autumn sowing increased root mass in the 0–10 cm layer by 0.085–0.889 tons (first year), 0.316–0.366 tons (second year), and 0.316–0.390 tons (third year). The spring sowing resulted in increases of 0.061–0.062, 0.230–0.341, and 0.304–0.379 t ha<sup>-1</sup>, respectively. The consistently lower root mass observed in severely eroded soils confirms that erosion intensity constrains root development, although mineral fertilizers partially mitigate these adverse effects by improving nutrient supply and root growth dynamics (Sleugh *et al.*, 2000; Sadigov and Mustafayev, 2024).

These results further revealed that both sowing times of sainfoin (*Onobrychis Adans.*) and soil erosion levels significantly influence the effectiveness of mineral fertilizers on root development, with autumn sowing generally resulting in higher root mass accumulation than with spring sowing. Across varying degrees of soil erosion and both sowing periods, the root mass of the plant increased in response to the different rates and combinations of mineral fertilizers applied. However, the most favorable results emerged with the N<sub>45</sub>P<sub>60</sub>K<sub>30</sub> application rate in the third year of the study, where a marked increase was evident in root mass compared with the unfertilized control plots.

Overall, the findings from the three-year investigation enunciated that in moderately and severely eroded gray-brown soils, mineral fertilizers consistently enhanced the root mass accumulation in the sowing layer, with the greater effects recorded in the third year of study. The mineral nutrients' application increased the concentration of readily available nutrients in the root zone, thereby ensuring more balanced plant nutrition and contributing to the robust development of

the root system in sainfoin (*Onobrychis* Adans.) (Sadigov *et al.*, 2026b).

In the mountainous regions of the republic, insufficient attention has persisted to the cultivation of perennial leguminous grasses. The absence of sainfoin cultivation on mountain slopes has intensified erosion processes, resulting in the loss of soil fertility and the removal of large arable areas. Each year, significant crop losses occur on the northeastern slopes of the Lesser Caucasus, where the limited crop cultivation further reduces overall productivity. Yet, in areas exposed to erosion and at risk of being removed from crop rotation, the introduction of perennial leguminous grasses can restore the soil fertility and develop favorable conditions for achieving higher yields. Provided, there is the support of mineral fertilizers applied at appropriate rates and ratios. Numerous studies have demonstrated that perennial legumes, such as sainfoin, improve soil fertility through biological nitrogen fixation, increased organic matter input, and enhanced soil structure, thereby reducing erosion risks when combined with balanced mineral fertilization (Sleugh *et al.*, 2000; Sadigov and Mustafayev, 2024).

In mountainous agricultural zones, long-term research has shown the application of simple and complex mineral fertilizers within recommended norms leads to substantial improvements in crop productivity (Sadigov *et al.*, 2024). For instance, on moderately eroded carbonate-washed mountain black soils, potato yields increased by 0.113–0.433 t ha<sup>-1</sup> (12.47%–47.79%). On moderately eroded gray-brown soils, winter wheat yields rose by 0.035–0.085 t ha<sup>-1</sup> (17.07%–41.46%), while on moderately eroded ordinary mountain gray-brown soils, the said increase ranged from 0.038 to 0.065 t ha<sup>-1</sup> (23.17%–39.63%). Mineral fertilizer application enhances the nutrient regime of soils with varying erosion intensities, maintaining adequate moisture and improving the soil structure. This further promotes favorable air-water permeability for root development, which subsequently supports vigorous growth aboveground. Plants grown under such conditions exhibit greater height, larger foliage, robust stems, and well-

developed branching (Sadigov and Macnunlu, 2023; Didehban *et al.*, 2025).

However, the effectiveness of mineral fertilizer use depends on accurately determining the appropriate application rates and selecting suitable fertilizer types for each sowing period. Ensuring this requires strict adherence to agrotechnical practices and proves it as one of the most critical considerations for sustainable crop production in erosion-prone mountain regions (Sadigov and Mustafayev, 2024). In addition to its agronomic and soil-protective properties, sainfoin (*Onobrychis* Adans.) possesses considerable value as a high-quality forage crop. Its dried biomass is soft and highly palatable, allowing for efficient digestion by livestock. The sainfoin plant is also rich in essential vitamins and bioactive compounds that contribute to improved nutritional balance in animal diets. Regular feeding with sainfoin improves livestock health, strengthens immune responses, and reduces the incidence of diseases, thereby decreasing mortality and overall herd weakness (Sadigov *et al.*, 2024).

Sainfoin (*Onobrychis* Adans.) is also well-known to improve the productive performance of dairy animals by supporting better digestion and metabolic efficiency. These advantages develop the favorable conditions for farming communities, enabling higher livestock productivity and contributing to stable and sustainable agricultural outcomes. Numerous studies have demonstrated that sainfoin (*Onobrychis* Adans.) possesses the highest nutritional values as a forage crop. Before flowering, its biomass contains approximately 22.0% protein and 25.1% cellulose; at the onset of flowering, these values were 20.0% and 25.8%, respectively; and at 50% flowering, the protein content was 18.8% with 28.1% cellulose. These figures highlighted its superior feed quality and the pivotal role in meeting livestock nutritional needs. The high protein content and favorable fiber composition of sainfoin make it a valuable forage for improving rumen function, feed intake, and overall metabolic efficiency in dairy animals. In addition to its nutritional quality, sainfoin contains condensed tannins that enhance protein utilization and

reduce digestive disorders, contributing to improved animal productivity and health (Mueller-Harvey, 2006; Waghorn, 2008, Sadigov *et al.*, 2026c; Mehdiyeva *et al.*, 2026).

However, soil erosion exerts a negative influence on the physiological processes and overall quality of sainfoin. In the absence of targeted anthropogenic interventions—particularly those aimed at enhancing soil fertility and crop productivity—intense erosion can degrade the cultivated areas, reduce nutrient availability, and cause visible stress symptoms in crop plants, such as leaf discoloration. Such crop deterioration negatively affects the forage quality and complicates consumption by livestock (Ayubov *et al.*, 2025; Sadigov *et al.*, 2025, 2026a).

The results revealed that the application of mineral fertilizers at appropriate types and rates positively affects plant growth and development and fodder quality. Forage quality indicators also vary according to the severity of soil erosion: in moderately eroded soils, forage quality parameters were consistently higher than in severely eroded soils. This difference was primarily ascribable to the reduced availability of essential nutrients, especially mobile nutrient forms in soils subjected to more intensive erosion processes. In severely eroded soils, nutrient losses reduce the availability of essential elements, which directly impacts both biomass production and nutritive value. (Haynes and Naidu, 1998; Sadigov *et al.*, 2026d).

Mineral fertilizers with recommended rates promote the rapid decomposition of plant roots in the soil, leading to the desired improvement in soil fertility. However, excessive application of fertilizers accelerates root decay to a degree that can ultimately harm plants. Proper fertilization enhances the development of lateral roots and rhizomes in perennial leguminous grasses, resulting in an increased total root biomass in the soil. This, in turn, contributes to a more uniform distribution of organic matter within the upper soil layer and improves the soil's agrochemical properties, including nutrient availability and overall soil fertility.

## RECOMMENDATIONS

The application of optimized mineral fertilizers should be within justified norms—particularly the N<sub>45</sub>P<sub>60</sub>K<sub>30</sub> combination—to ensure optimal root development, soil fertility restoration, and forage quality. Over- or under-application of mineral fertilizers must not occur to prevent plant stress and soil degradation.

Prioritize the autumn sowing in eroded areas, as it consistently resulted in higher root mass accumulation than with spring sowing. Therefore, this practice has a higher recommendation for achieving better plant establishment and improving resistance to erosion.

Sainfoin cultivation should entail wide introduction and promotion in mountainous and foothill zones experiencing moderate to severe erosion. Its extensive root system and high-quality forage value prove it as an ideal species for soil stabilization and productivity.

Long-term soil restoration programs require wider implementation in regions where soil erosion is widespread, with perennial leguminous grasses integrated into crop rotation systems to enhance the organic matter content, improve soil structure, and promote long-term ecological resilience.

Regular soil analysis should be sustainable to monitor nutrient availability, especially mobile nutrient forms in the eroded soils. This allows for precise fertilizer adjustments and prevents nutrient imbalances.

Farmers and agricultural specialists should follow appropriate agrotechnical measures, including proper seedbed preparation, timely sowing, and controlled fertilizer application, to maximize crop growth and soil rehabilitation outcomes.

Agricultural extension services should offer training programs to the farming communities in the mountainous regions, emphasizing the importance of perennial legumes, correct fertilizer use, and erosion control strategies.

## CONCLUSIONS

Results showed sainfoin (*Onobrychis* Adans.) cultivation should have support from appropriate use of mineral fertilizers, which significantly improved soil fertility and crop performance under eroded mountain gray-brown soils. Fertilization enhanced lateral root and rhizome development and total root biomass, improved soil structure, and developed better air-water and nutrient conditions. The autumn sowing with moderately eroded soils showed a remarkable response. The fertilizer rate ( $N_{45}P_{60}K_{30}$ ) consistently displayed considerable positive effects over three years, leading to improved aboveground growth, higher yields, and better forage quality.

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