EFFECTS OF DIFFERENT LEONARDITE DOSES ON FORAGE YIELD, QUALITY AND BOTANICAL COMPOSITION OF NATURAL RANGELANDS IN A SEMI-ARID ENVIRONMENT

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Abstract. This study was conducted to investigate the effects of different leonardite doses on dry matter yield, forage quality traits and botanical composition in the natural rangelands of the Tek Tek Mountains, located in Şanlıurfa province, Türkiye. Fort this reason, the experiments were arranged in the natural rangeland area according to a randomized complete block design with three replications during the two consecutive years, 2017 and 2018. In addition to the control treatment (0 dose), in which no leonardite was applied, eight different leonardite doses (250, 500, 750, 1000, 1250, 1500, 1750, and 2000 kg ha^{-1}) were tested to determine effects of different leonardite doses. The study results revealed that leonardite significantly influenced dry matter yield, crude protein content, acid detergent fiber (ADF), neutral detergent fiber (NDF), and the botanical composition of the rangeland. The highest dry matter yield was obtained at a dose of 1000 kg ha^{-1}, while crude protein content peaked at 500 kg ha^{-1}, with higher doses causing a decline in forage quality. ADF and NDF values decreased with increasing leonardite doses up to 1500 kg ha^{-1}, suggesting improved digestibility, although excessive doses reversed this trend. Moreover, leonardite application altered botanical composition by increasing the proportion of grasses and legumes and reducing other plant families, with optimal effects observed at moderate doses. The study concludes that moderate leonardite doses, particularly between 500 and 1000 kg ha^{-1}, can be recommended as an effective soil amendment to improve the productivity, quality, and species composition of semi-arid natural rangelands. However, caution is advised against excessive application, which may adversely affect forage quality.
Keywords: *ADF, crude protein, grasses, humic acid, legumes, NDF*

Introduction

Natural rangelands are globally important ecosystems and provide abundant and inexpensive quality roughage for livestock, supporting biodiversity, and contributing to soil health and carbon sequestration, particularly in semi-arid regions. However, these ecosystems often face significant degradation due to factors such as overgrazing, climate change, and nutrient depletion, leading to reduced productivity, diminished forage quality, and shifts in botanical composition towards less desirable species (Sayar et al., 2015; Polat et al., 2018). Improving the productivity and sustainability of these degraded

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rangelands is paramount for food security and ecological balance (Unal et al., 2017; Kara, 2020).

Soil amendments play a vital role in restoring and enhancing the fertility of rangeland soils. Among these, leonardite, a naturally oxidized lignite rich in humic and fulvic acids, has gained considerable attention as a powerful organic amendment (Tan, 2003; Ratanaprommanee et al., 2017; Akimbekov et al., 2020). Humic substances in leonardite are known to improve soil physical properties such as water-holding capacity and aeration, enhance nutrient availability through chelation, stimulate microbial activity, and directly promote plant growth by influencing physiological processes (Chen and Aviad, 1990; Dursun et al., 2002; Sanlı et al., 2013). Previous studies have demonstrated the positive effects of leonardite on various agricultural crops, including increases in yield, nutrient uptake, and stress tolerance. In the context of forage production, leonardite application has been shown to improve hay yield and dry matter content in diverse forage species (Yolcu et al., 2011; Nazli et al., 2014).

Despite the established benefits of leonardite in cultivated systems, its specific effects on the complex dynamics of natural rangeland ecosystems, particularly in semi-arid environments like Southeastern Türkiye, are not as extensively documented. Understanding how different leonardite application rates influence key forage characteristics—such as dry matter yield, crude protein content, and fiber components (ADF and NDF)—as well as the overall botanical composition, is critical for developing sustainable rangeland management strategies. Changes in botanical composition, specifically the proportions of grasses, legumes, and other plant families, directly impact the nutritional value and palatability of available forage for grazing animals.

While previous research has extensively explored the positive impacts of leonardite application on cultivated crops, little is known about its specific effects on natural rangeland ecosystems, especially within the context of semi-arid climates. The majority of existing literature focuses on controlled agricultural environments, leaving a significant gap regarding the complex interactions between leonardite and the diverse plant communities of native rangelands. This study fills this critical knowledge gap by providing the first comprehensive, two-year investigation into how varying leonardite doses affect forage yield, quality, and the intricate botanical composition of a semi-arid natural rangeland. Our findings thus provide novel and essential insights for developing sustainable rangeland management strategies in these vulnerable ecosystems.

Materials and methods

The experiments of the research

The research was conducted in the natural rangelands of the Tek Tek Mountains, located within the borders of Şanlıurfa province in the Southeastern Anatolia Region of Türkiye, during the years 2017 and 2018. The rangeland area where the study was carried out is a protected natural rangeland. The experimental design was established as a randomized complete block design with three replications. The experimental plots used in the study measured 2 meters in width and 3 meters in length, covering a total area of 6 m² per plot.

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Properties of the used leonardite material and the applied doses

In the study, a control treatment without leonardite application (0 dose) was included alongside eight different leonardite doses (250 kg ha^{-1}, 500 kg ha^{-1}, 750 kg ha^{-1}, 1000 kg ha^{-1}, 1250 kg ha^{-1}, 1500 kg ha^{-1}, 1750 kg ha^{-1} and 2000 kg ha^{-1}). The leonardite doses were applied to the experimental plots in both years during November. The powdered leonardite material was uniformly distributed across the plots and incorporated into the rangeland soil using a rake to ensure proper mixing. The physical and chemical properties of Leonardite used in the research are given in *Table 1*. The leonardite material used in this study was characterized by high organic matter content, totaling 40% as determined by combustion at 550°C. The pH value of the leonardite ranged between 5.7 and 7.7, indicating that the material is weakly acidic to neutral, which is favorable for improving soil structure and nutrient availability. Furthermore, the total humic and fulvic acid content of the leonardite was measured at 40%, reflecting its significant potential to enhance soil fertility and stimulate plant growth through improved nutrient uptake and soil microbial activity. The moisture content of the leonardite was 18.7% when measured at 105°C, which is consistent with typical moisture levels for such organic soil amendments. Additionally, the porosity of the material was determined to be 33%, a property that can contribute to improved soil aeration, water retention, and root development. These characteristics collectively indicate that the leonardite applied in this study possesses favorable physical and chemical properties for use as a soil amendment in rangeland ecosystems.

Table 1. *Physical and chemical properties of leonardite material used in the research*

Leonardite properties	Amount/Value
Organic matter (550°C combustion)	40%
pH (26°C)	5.7 -7.7
Total humic and fulvic acid	40%
Moisture content (105°C)	18.7%
Porosity	33%

Soil properties of the rangeland area

The soil analysis results of the rangeland area were presented in the *Table 2*. The soil analsis results revealed that the upper 0–30 cm soil layer has a clay-loam texture, which is generally favorable for water retention and nutrient holding capacity. The soil exhibited a water saturation rate of 64%, indicating moderate water-holding potential.

Table 2. *Soil analysis results of the rangelands where the study was conducted*

Soil Depth (cm)	Soil Texture	Saturation with Water (%)	pH in Saturated Soil	Lime ($CaCO_3$) (%)	Phosphorus (P_2O_5) (kg/da)	Potassium (K_2O) (kg/da)	Organic Matter (%)
0–30	Clay-Loam	64	7.87	23.06	1.19	89.27	1.03

The pH value of the saturated soil was measured at 7.87, suggesting slightly alkaline conditions, which are typical for calcareous soils in semi-arid regions. Consistent with this, the lime ($CaCO_3$) content was relatively high at 23.06%, which may influence

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nutrient availability, particularly phosphorus. The available phosphorus (P_2O_5) content was found to be low, at 1.19 kg/da, potentially limiting plant growth if not amended. Potassium (K_2O) content was determined as 89.27 kg/da, providing a moderate level of this essential macronutrient. The organic matter content of the soil was 1.03%, which is relatively low and reflects the degraded condition of natural rangelands typical of the Southeastern Anatolia Region. These findings indicate that the rangeland soils possess certain limitations in terms of nutrient availability and organic matter content, making them suitable for assessing the potential benefits of leonardite applications.

Climatic properties of the rangeland area

The climatic characteristics of the study area for the years 2017, 2018, and the long-term averages were presented in *Table 3*. The climatic data for the Tek Tek Mountains rangeland, where the study was conducted, indicated significant annual and seasonal variation in precipitation, temperature, and relative humidity during the experimental years (2017 and 2018) compared to long-term averages. In 2017, total annual precipitation amounted to 312.3 mm, which was lower than the long-term average of 455.2 mm, while in 2018, precipitation was even lower at 196.4 mm, indicating pronounced drought conditions.

Table 3. *Long-term and experimental years' average climatic data for the study area*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Now	Dec	
Years	**Monthly Total Precipitation (mm)**												**Total**
2017	95,6	17,1	13,0	27,1	12,3	0,6	0,2	0,0	0,0	22,0	23,3	101,1	312,3
2018	9,0	1,8	55,2	79,2	7,2	0,0	0,0	0,0	0,0	17,1	17,4	9,5	196,4
Long-Years Avg.	85,7	71,4	64,1	46,8	28,1	3,6	0,6	0,8	3,3	27,4	46,0	77,4	455,2
	Monthly Average Temperature (°C)												**Mean**
2017	4,7	11,6	13,6	20,6	23,2	29,8	33,0	33,2	26,4	22,1	12,6	5,4	19,7
2018	5,4	7,7	12,7	16,6	22,9	29,7	34,2	32,2	29,6	20,5	13,4	10,3	19,6
Long-Years Avg.	5,7	7,0	11,0	16,2	22,3	28,2	31,9	31,2	26,8	20,2	12,7	7,5	18,4
	Monthly Average Relative Humidity (%)												**Mean**
2017	70,3	61,8	50,3	36,1	38,3	28,0	25,4	30,6	32,1	35,9	42,9	70,1	43,5
2018	61,9	45,3	57,1	50,2	39,0	27,0	22,9	35,7	28,8	36,9	56,0	60,2	43,4
Long-Years Avg.	70,3	66,9	60,4	56,2	44,9	32,8	30,0	33,1	35,8	46,4	59,9	69,9	50,6

Mean annual temperatures during the experimental years (19.7 °C in 2017 and 19.6°C in 2018) were slightly higher than the long-term average of 18.4°C, reflecting warmer than average growing seasons. Relative humidity was generally lower than long-term averages, particularly in 2018, suggesting drier atmospheric conditions during the vegetation period. These climatic conditions, particularly the below-average rainfall and higher temperatures, are typical of semi-arid regions and likely influenced both plant growth dynamics and the response of rangeland vegetation to leonardite applications observed in this study.

The investigated traits

The forage harvesting in the rangeland plots was carried out during the first week of May, coinciding with the flowering stage of grass species. In each plot, all the forage present was harvested entirely. The harvested forage was weighed immediately without

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allowing for moisture loss, and the fresh forage yield of the plots was determined. To calculate dry matter yields, 500 g of fresh grass samples were taken from each plot. Dry matter yields were determined after fresh samples were oven-dried at 70 °C for 48 h and then ground to pass through a 1-mm sieve for the analysis of crude protein (Sayar et al., 2014). The Kjeldahl method was used to determine the total N and the crude protein content of both sole forages and mixtures were determined as 6.25 x N (AOAC, 1995). Acid detergent fiber (ADF) ratio and neutral detergent fiber (NDF) ratio analyses were undertaken according to ANKOM (1997). In order to determine botanical composition of the plots, four quadrats, each measuring 0.5 × 0.5 m^2, were randomly placed within each experimental plot. Then, the plant species within each plot were classified into three groups: grasses, legumes, and other plant families.

The statistical analyses

The data obtained from the study were subjected to analysis of variance (ANOVA) using the JMP statistical software package (SAS, 2002). Means found to be statistically significant were grouped according to the LSD (Least Significant Difference) multiple comparison test at the 5% significance level.

Results

Dry matter yield

The study results showed that statistically highly significant ($P<0.01$) differences were found among the different leonardite doses applied in the natural the rangelands of Tek Tek Mountains, Şanlıurfa, Türkiye, for dry matter yield trait. However, years and year × dose interactions were found to be statistically insignificant for dry matter yield (*Table 4*). According to the two-year averages in the study, means of dry matter yields among the leonardite doses varied between 463.3 kg ha^{-1} and 1485.8 kg ha^{-1}. It was determined that 1000, 1250, 1500, 1750 and 2000 kg ha^{-1} doses were statistically more productive than 0 (Control), 250, 500 and 750 kg ha^{-1} doses in terms of dry matter yield. Statistically, no difference was observed between 1000 kg ha^{-1} and 2000 kg ha^{-1} in terms of dry matter yield of the rangelands (*Table 4*).

Crude protein content

The study results indicated that there were statistically highly significant ($P<0.01$) differences among the different leonardite doses applied in the natural the rangelands of Tek Tek Mountains, Şanlıurfa, Turkey, for crude protein content trait. However, years and year × dose interactions were found to be statistically insignificant for crude protein content trait (*Table 4*). According to the two-year averages in the study, means of crude protein content among the leonardite doses varied from 7.50% to 11.25%. Additionally, it was determined that the crude protein content in all leonardite doses was higher than the control (0 dose) treatment. However, it was determined that 500, 750 ve 1000 kg ha^{-1} leonardite doses, had statistically higher crude protein contents than the other leonardite doses. Leonardite doses significantly affected the crude protein content of rangeland forages It was determined that there were decreases in crude protein content at leonardite doses above 1000 kg ha^{-1} (*Table 4*).

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***Table 4.** Means and groups of dry matter yield and crude protein content traits with effect of different leonardite doses in the rangelands of Tek Tek Mountains, Şanlıurfa, Türkiye*

Leonardit Doses (kg ha^{-1})	**Dry matter yield (kg ha^{-1})**						**Crude protein content (%)**					
	2017		**2018**		**Mean**		**2017**		**2018**		**Mean**	
0	645.0	e-g	281.7	g	463.3	c	7.50	f	7.50	f	7.50	f
250	356.4	f-g	588.6	e-g	472.5	c	9.80	b-e	9.50	b-e	9.65	b-e
500	765.0	d-e	690.0	e-f	727.5	c	10.70	a-c	9.90	a-e	10.30	a-c
750	1186.0	b-c	1096.7	c-d	1141.3	b	11.50	a	11.00	a-b	11.25	a
1000	1528.3	a-b	1443.3	a-c	1485.8	a	11.00	a-b	10.02	a-e	10.51	a-b
1250	1365.0	a-c	1280.0	a-c	1322.5	a-b	10.33	a-d	9.50	b-e	9.92	b-d
1500	1570.0	a-b	1400.0	a-c	1485.0	a	9.70	b-e	8.70	d-f	9.20	c-e
1750	1301.7	a-c	1213.3	b-c	1257.5	a-b	9.20	c-e	8.60	e-f	8.90	d-e
2000	1714.7	a	1255.6	b-c	1485.1	a	8.24	e-f	8.76	d-f	8.50	e-f
Mean	1159.1		1027.7		1093.4		9.77		9.28		9.52	
CV (%)	22.5						10.59					
LSD (0.05)												
Years	ns						ns					
Leonardit Doses	286.2**						1.18**					
Year × Leonardit Doses	ns						ns					

**, significant at P ≤ 0.01; ns, non-significant

Acid detergent fiber (ADF) ratio

The study results indicated that there were statistically highly significant (P<0.01) differences between years and among the different leonardite doses applied in the natural the rangelands of Tek Tek Mountains, Şanlıurfa, Türkiye for ADF ratio trait. However, years and year × dose interactions were found to be statistically insignificant (P>0.05) for ADF ratio trait (*Table 5*). According to two-year averages, ADF rates varied between 32.75% and 42.75% among leonardite doses. The highest ADF value was observed in the control treatment (0 dose) where no leonardite was applied. The lowest ADF value was recorded at the 1500 kg ha^{-1} leonardite dose. However, ADF values increased again at higher leonardite doses of 1750 and 2000 kg ha^{-1}, reaching 36.45% and 36.13%, respectively. A significant difference was also observed between the years (P < 0.01), with higher ADF values recorded in 2018 compared to 2017.

Neutral detergent fiber (NDF)

The study results indicated that while a statistically significant difference at the level of 0.05 was detected between the years in the study, a statistically significant difference at the level of 0.01 was detected among the different leonardite doses applied in the natural the rangelands of Tek Tek Mountains, Şanlıurfa Türkiye for NDF ratio trait. However, years and year × dose interactions were found to be statistically insignificant (P>0.05) for NDF ratio trait. Moreover, it was determined that NDF ratios recorded in 2018 were found to be higher than those of 2017. According to two-year averages, NDF rates varied between 59.00% and 72.00% among leonardite doses. While the highest NDF value was determined in the control application where no leonardite was applied, the lowest NDF rate was determined in the 1500 kg ha^{-1} treatment. NDF ratios showed a decreasing trend with increasing leonardite doses up to 1500 kg ha⁻¹. At higher doses of 1750 and 2000 kg ha⁻¹, NDF ratios increased again, reaching 64.70% and 64.36%, respectively (*Table 5*).

Table 5. *Means and groups of acid detergent fiber (ADF) ratio and neutral detergent fiber (NDF) ratio traits with effect of different leonardite doses in the rangelands of Tek Tek Mountains, Şanlıurfa, Türkiye*

Leonardit Doses ($kg\ ha^{-1}$)	Acid detergent fiber (ADF) ratio (%)				Neutral detergent fiber (NDF) ratio (%)			
	2017	2018	Mean		2017	2018	Mean	
0	42.00	43.50	42.75	a	71.00	73.00	72.00	a
250	38.00	39.50	38.75	b	65.00	65.00	65.00	b
500	37.50	39.00	38.25	b-c	64.00	66.00	65.00	b
750	36.00	37.50	36.75	b-d	64.00	66.00	65.00	b
1000	35.00	36.50	35.75	d-e	63.40	63.40	63.40	b-c
1250	33.00	34.50	33.75	e-f	59.00	61.00	60.00	c-d
1500	32.00	33.50	32.75	f	58.00	60.00	59.00	d
1750	35.70	37.20	36.45	b-d	63.70	65.70	64.70	b
2000	34.94	37.33	36.13	c-e	62.61	66.12	64.36	b
Mean	36.02 B	37.61 A	36.81		63.41 B	65.14 A	64.27	
CV (%)	5.44				4.68			
LSD (0.05)								
Years	0.11**				1.66*			
Leonardit Doses	2.35**				3.53**			
Year × Leonardit Doses	ns				ns			

*, significant at P ≤ 0.05; **, significant at P ≤ 0.01; ns, non-significant

Effect of leonardit doses on rangeland botanical composition

The study results revealed that the differences between the leonardite doses was found to be statistically highly significant (P<0.01) for grass species ratio (%), legume species ratio (%) and other families species ratio traits in botanical composition of the rangeland. However, the interaction between the years and year x leonardite doses interaction were found to be as insignificant for the three traits. In the study, among the leonardite doses, the following ranges were determined in the rangeland botanical composition; grass species ratio varied between 86.93% amd 94.94%, legume species ratio varied between 0.98% and 2.92% and other families species ratio varied between 3.53% and 12.19%. Leonardite doses positively affected the increase in grass species and legume species ratios in the rangeland vegetation, but caused a decrease in the proportion of plants in other families. The highest rate in the grass family was found at doses between 1000 kg ha^{-1} and 1750 kg ha^{-1}, while the highest rate in the legume family was found between 500 kg ha^{-1} and 1000 kg ha^{-1}. On the other hand, the highest proportion of plants from other families was found in the 0 (control) dose (*Table 6*).

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Table 6. *Means and groups of grass species ratio, legume species ratio and other families species ratio traits with effect of different leonardite doses in the rangelands of Tek Tek Mountains, Şanlıurfa, Türkiye*

Leonardit Doses (kg ha^{-1})	**Grass species (%)**			**Legume species ratio (%)**			**Other families species ratio (%)**		
	2017	**2018**	**Mean**	**2017**	**2018**	**Mean**	**2017**	**2018**	**Mean**
0	87.58 h	86.28 h	86.93 e	0.89 f	0.87 f	0.88 e	11.53 a	12.85 a	12.19 a
250	90.95 f-g	91.59 d-g	91.27 d	1.56 c-f	1.93 b-f	1.75 b-d	7.48 b	6.48 b-d	6.98 b
500	90.67 g	91.45 e-g	91.06 d	1.99 b-e	2.45 a-d	2.22 a-c	7.34 b-c	6.10 b-f	6.72 b-c
750	91.54 e-g	92.07 c-g	91.80 c-d	2.67 a-b	3.16 a	2.92 a	5.79 b-g	4.77 d-h	5.28 b-d
1000	92.75 b-g	93.84 a-e	93.30 a-c	2.30 a-d	2.55 a-c	2.42 a-b	4.95 c-h	3.62 g-h	4.28 d-e
1250	93.36 a-f	94.12 a-c	93.74 a-b	1.86 b-f	2.14 a-e	2.00 b-d	4.78 d-h	3.74 f-h	4.26 d-e
1500	94.57 a-b	95.32 a	94.94 a	1.40 d-f	1.66 b-f	1.53 c-e	4.04 e-h	3.02 h	3.53 e
1750	93.22 a-f	93.97 a-d	93.59 a-b	1.19 e-f	1.52 c-f	1.35 d-e	5.59 b-g	4.51 d-h	5.05 c-e
2000	92.41 b-g	92.09 c-g	92.25 b-d	0.99 e-f	1.54 c-f	1.26 d-e	6.60 b-e	6.37 b-d	6.49 b-c
Mean	91.89	92.30	92.10	1.65	1.98	1.81	6.46	5.72	6.09
CV (%)	1.57			3.57			2.38		
LSD (0.05)									
Years	ns			ns			ns		
Leonardit Doses	1.71**			0.75**			1.68**		
Year × L. Doses	ns			ns			ns		

*, significant at P ≤ 0.05; **, significant at P ≤ 0.01; ns, non-significant

Discussions

The study results showed that there were statistically highly significant (P<0.01) differences among the applied leonardite doses for all of the investigated traits, while the year x leonardite dose interactions were insignificant (P>0.05) for all of the traits examined. In fact, insignificance of year x leonardite doses interactions indicated that the relative effectiveness of the different leonardite application rates remained consistent across both the dry year (2017) and the year with more favorable rainfall (2018). This strengthens the reliability of our conclusions and suggested that the recommended doses can be applied with a high degree of confidence for long-term rangeland management, regardless of annual climatic variability. This finding significantly enhances the practical applicability of our results for farmers and land managers in semi-arid regions facing unpredictable rainfall patterns.

The present study demonstrated that leonardite application exerts multifaceted effects on semi-arid rangeland ecosystems, simultaneously influencing dry matter yield, nutritional quality, fiber composition, and botanical diversity. Taken together, these results underscore the potential of leonardite as a valuable soil amendment for enhancing rangeland productivity and sustainability, provided that it is applied at optimal doses. In terms of productivity, leonardite significantly increased dry matter yield, with the most substantial improvements observed at moderate application levels (1000 kg ha^{-1}) (*Table 4*). This finding aligns with previous studies that reported similar yield-enhancing effects of leonardite in various forage species (Yolcu et al., 2011; Nazli et al., 2014; Solmaz et al., 2018). The positive impact of leonardite is attributable to its role in improving soil fertility and water retention, thereby supporting higher biomass production

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under semi-arid conditions. Importantly, these effects were consistent across years with contrasting rainfall patterns, as the year × leonardite interaction was insignificant (P>0.05), confirming that environmental variability did not alter treatment rankings (Sayar et al., 2013). This strengthens the reliability of the results and highlights their practical relevance for long-term management in regions with unpredictable rainfall (Sayar et al., 2015; Polat et al., 2018).

Beyond yield, leonardite also influenced forage quality parameters, notably crude protein content and fiber fractions. The most economical and ideal dose for crude protein content was observed at 500 kg ha^{-1} (*Table 4*). These results are consistent with earlier reports indicating significant improvements in crude protein with leonardite or other organic amendments in different crops (Fateh et al., 2009; Yolcu et al., 2011; Nazli et al., 2018). However, higher applications led to a decline in protein concentration, likely due to a dilution effect associated with excessive vegetative growth and nutrient binding by humic substances. In addition, it was observed that the crude protein values determined in the study were also compatible with crude protein content findings determined by Severeoglu and Gullap (2020) in rangeland forages. Also, Basbag et al. (2021) and Sayar et al. (2022) emphasized the importance of crude protein content on forage quality. Similarly, fiber quality indicators showed dose-dependent improvements. Both acid detergent fiber (ADF) and neutral detergent fiber (NDF) values declined with increasing leonardite doses up to 1500 kg ha^{-1} (*Table 5*), suggesting improved digestibility and greater intake potential for grazing animals (Sayar et al., 2014). However, at very high doses (1750–2000 kg ha^{-1}), ADF and NDF values slightly increased (*Table 5*), indicating diminishing or even adverse effects on intake and digestibility of forages. These findings align with previous work reporting that moderate leonardite applications can reduce fiber fractions and enhance forage quality, while excessive doses may reverse these benefits (Yolcu et al., 2011; Nazli et al., 2014).

Changes in botanical composition further reinforce this dose-dependent dynamic. The research results indicated that most of the rangeland plants studied were species in the *Poaceae* or *Grasses* family. Consisting with earlier studies noting that rangeland vegetation in Southeastern Anatolia is dominated by *Poaceae* species (Sayar et al., 2015; Tasdelen and Ozyazıcı, 2022). Leonardite promoted the growth of grasses and legumes while reducing the abundance of species from other families. The highest grass ratio was recorded between 1000–1750 kg ha^{-1}, while legumes peaked at 500–1000 kg ha^{-1} (*Table 6*). The observed shift is supported by the well-documented effects of humic substances on enhancing soil fertility, nutrient availability, and plant vigor (Chen and Aviad, 1990; Dursun et al., 2002; Tan, 2003; Sanlı et al., 2013; Ratanaprommanee et al., 2017; Akimbekov et al., 2021). Improved soil conditions not only benefit grasses but also create favorable environments for legumes by enhancing phosphorus availability and nodulation capacity, thus contributing to nitrogen cycling and rangeland resilience.

A limitation of this study is its short-term scope, which does not allow for assessment of the long-term impacts of leonardite on soil health, forage quality, and plant community stability. Although the findings were consistent across two years with differing rainfall, broader climatic variability and extreme events common in semi-arid regions may influence leonardite’s effectiveness in ways not fully captured here. Additionally, leonardite’s chemical composition can vary depending on its source and processing, which may affect its nutrient-binding capacity and overall performance. These uncertainties emphasize the need for long-term, multi-site studies under diverse environmental conditions to confirm the reliability and general applicability of the results.

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Repeated leonardite application can improve soil health in the long term by enhancing organic matter, nutrient availability, water retention, and microbial activity, which supports productive grasses and nitrogen-fixing legumes (Chen and Aviad, 1990; Akimbekov et al., 2021). However, excessive or prolonged use may cause nutrient imbalances, such as nitrogen dilution or mineral chelation, leading to reduced forage protein quality and altered plant competition. These shifts could favor dominance of fast-growing grasses, reduce biodiversity, and potentially affect microbial community structure or soil pH. Therefore, the sustainability of repeated leonardite use depends on careful dose management to enhance fertility without undermining plant community stability.

Optimizing leonardite use in rangeland restoration carries important policy and sustainability implications, particularly for semi-arid regions where soil degradation, low forage quality, and climatic variability pose major challenges to livestock-based livelihoods. By enhancing soil fertility, water retention, and forage nutritional value at moderate doses, leonardite can support more resilient grazing systems, reducing the need for synthetic inputs and aligning with sustainable land management goals. From a policy perspective, integrating leonardite into rangeland improvement programs could contribute to climate adaptation strategies, food security, and rural development by sustaining forage resources under variable rainfall conditions. Furthermore, its role in promoting legumes and improving nutrient cycling supports ecosystem services such as soil carbon sequestration and biodiversity maintenance. However, to ensure sustainability, policies should emphasize guidelines for optimal application rates, quality standards for leonardite products, and monitoring frameworks to prevent overuse or ecological imbalances.

Conclusions

In conclusion, the combined findings indicated that moderate leonardite doses (500–1000 kg ha^{-1}) improved dry matter yield, crude protein content, and forage digestibility while fostering a more desirable botanical composition. However, the benefits were strongly dose-dependent, with moderate applications offering optimal outcomes and excessive applications leading to diminishing or adverse effects. For farmers and land managers in semi-arid regions, these insights provide a practical framework for integrating leonardite into rangeland management strategies that enhance forage productivity, improve livestock nutrition, and sustain ecological balance in the face of climatic uncertainty. Additionally, highlighting leonardite as a cost-effective and ecologically sustainable amendment. Optimizing leonardite application can support both livestock production and broader rangeland restoration policies, thereby contributing to the long-term sustainability of semi-arid rangeland ecosystems.

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