



Effect of silicon and application of potassium on *Puccinellia distans* grown under saline-alkali conditions

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Received: 15/09/2025, Accepted: 22/12/2025

Abstract

Salinity and alkaline conditions are among the most important abiotic stress factors that limit plant growth and development, especially in arid and semi-arid areas. Indeed, approximately 30,000 hectares of plain land located in the Dumlu region of Erzurum cannot be adequately utilized due to high groundwater levels, salinity, and alkalinity. Reclaiming this type of soil is quite costly, and one of the prominent alternatives is to identify plant species and varieties that are tolerant to high soil salinity and ensure their cultivation in such areas. For this purpose, in our study, along with the halophyte plant *Puccinellia distans*, silicon dioxide (SiO₂) and potassium nitrate (KNO₃) fertilizers were used. The research was conducted in greenhouses at Atatürk University Faculty of Agriculture, using soil samples appropriately taken from four different sections of the affected region with varying salt content, according to a completely randomized experimental design. For this purpose, a total of 144 pots (4×1×4×3×3=144) were used across 4 different locations, with 1 halophyte plant *Puccinellia distans*, 4 different silicon (SiO₂) doses (0, 1, 2, and 4 mM), 3 different potassium nitrate (KNO₃) doses (0, 20, and 40 mM) with 3 replications. Plant height, number of main stems, number of leaves, fresh forage yield and dry matter yield, crude protein content and yield, and ADF and NDF contents were examined in the plants obtained at the end of the trial. As a result, a decrease in all yield and yield components was observed in plants grown under saline-alkali conditions compared to plants grown in normal soil. However, in saline-alkaline conditions, the application of silicon and potassium generally reduced the negative effects of salinity stress on the plant. The highest dry matter yield, crude protein content, and yield value were obtained from the application of 40 mM KNO₃ fertilizer without the addition of silicon. Based on these results, we can say that the plant *Puccinellia distans* is promising for the evaluation of saline-alkali areas with similar conditions, and that potassium fertilization in particular is effective in increasing its yield.

Keywords: *Puccinellia distans*, Salinity, Halophytes, Silicon, Alkali

Please cite this article as follows:

Kaynar, D., & Çomaklı, B. (2025). Effect of silicon and application of potassium on *Puccinellia distans* grown under saline-alkali conditions. *Journal of Biometry Studies*, 5(2), 45-52. <https://doi.org/10.61326/jofbs.v5i2.03>

1. Introduction

Salinity and alkalinity are among the most important abiotic stress factors that limit plant growth and development, especially in arid and semi-arid areas (Cui et al., 2021). Saline-alkali soils have poor physicochemical conditions, which damage the chemical, physical, and microbiological properties of the soil, thereby limiting crop growth (Zhao et al., 2020; Hao et al., 2021). Indeed, approximately 20% of the world's irrigated land is affected

by salinity and alkalinity, making this a significant problem for global agriculture and food security (Baloch et al., 2025). Therefore, reclaiming problematic lands like saline-sodic soils and bringing them back into agricultural production is of great importance for agricultural sustainability. Among the reclamation methods for this type of soil are physical, chemical, and biological methods such as sand mixing and mulching, the use of gypsum and humic acid, phytoremediation, and microbial reclamation,



as well as some modern technologies like genetic (Wang et al., 2023; Zhu et al., 2024) and electrokinetic reclamation (Reuss, 1809; Özentürk, 2022). However, the most economical of these alternatives is phytoremediation, which involves identifying and cultivating plant species and varieties, often halophytes, that are tolerant to high soil salinity in such areas (Amombo et al., 2022).

Actually, saline-alkali soil conditions restrict the growth of many cultivated plants and allow only a small fraction of the herbaceous species in the vegetation to grow. Similarly, in a study conducted to determine the forage plant species that could grow in the research area, it was observed that grasses were more resistant, while none of the examined plants (alfalfa, birdsfoot trefoil, white clover, tall fescue, meadow fescue, perennial ryegrass, tall oatgrass, and smooth brome) showed promise in the land soils (Tan et al., 2002). However, it has been reported that halophytic plants can be used in such marginal areas for the remediation of saline soils, and can also serve as an alternative animal feed-protein source (Li et al., 2019; Çınar et al., 2021; Behera & Ramachandran, 2021). *Puccinellia distans* is known as a salt-tolerant halophyte plant that can grow naturally in saline areas (Soleimannejad et al., 2019). Studies have shown that the plant is used in Iran for the reclamation of saline lands (Bandani & Abdolzadeh, 2007). Additionally, it has been reported to increase the productivity of saline lands and can be used as a forage crop in animal nutrition (Alshammary et al., 2004; Rao et al., 2017). In addition, recent studies have concluded that the combined use of biological and chemical methods in the reclamation of saline-alkali soils could be a more effective alternative (Cuevas et al., 2019).

It is known that the first application of phytoremediation for the reclamation of saline-alkali soils, using gypsum with green manure plants, was carried out by Kelley (1937). On the other hand, it is known that silicon (Si) and potassium (K) increase the tolerance of plants under abiotic stress, especially salinity, and improve growth (Abbas et al., 2015; Ahanger & Agarwall, 2017; Servet & Eşitken, 2018). It has been found that silicon increases plant salt tolerance by controlling the transport and accumulation of Na^+ and K^+ , which are the main salt tolerance mechanisms in plants under salinity stress (Zhu & Gong, 2014; Kınay & Erdem, 2022). In addition, potassium increases the tolerance of plants under salt stress due to its specific functions in important metabolic events such as plant water consumption, protein synthesis, energy metabolism, and photosynthesis (Li et al., 2017; Ahanger & Agarwall, 2017). For this purpose, it was aimed to

determine both the adaptation of the halophyte *Puccinellia distans* and the effect of the applications on yield and yield components in the plant, along with SiO_2 and KNO_3 fertilizers in the research area.

2. Material and Method

The research was conducted in the Dumlu (Erzurum) region in 2009-2010, using soil samples taken from four different locations with varying salt content, which were exposed to the degradation process and had agricultural potential. The samples were collected from the greenhouses of Atatürk University Faculty of Agriculture. Soil samples taken from a depth of 0-30 cm in the test field were air-dried, sieved thru a 4 mm sieve, and then placed in 15 cm diameter plastic pots with 1000 g of soil per pot. In the trial greenhouse conditions, according to the factorial design, the Completely Randomized Block design was used with 4 different locations (1. Location: N 40°01'13.4", E 041°20'54.1"; 2. Location: N 39°58'07.2", E 041°17'57.3", 3.location: N 39°59'07.6"; E 041°17'56.7", 4.location: N 39°58'49.9", E 041°21'24.8"); 1 plant (*Puccinellia distans*), 4 different silicon doses (0, 1, 2, and 4 mM), 3 different KNO_3 doses (0, 20, and 40 mM) were carried out in a total of 144 pots ($4 \times 1 \times 4 \times 3 \times 3 = 144$) with 3 replications over a period of two years. However, since plant emergence occurred in only two soil groups (1 and 2), the experiment was conducted with these two soil type, and these two soil type were also evaluated in the statistical analysis.

The analyzes of the soils were conducted in the laboratories of the Soil Science Department in Faculty of Agriculture, according to Kacar (1994). Some properties of the problematic and soil materials used in the experiment are shown in Table 1. Analysis of soil samples revealed that soil sample 1 is normal, samples 2 and 3 are saline-alkaline, and sample 4 is alkaline soil (Table 1). It is known that the soils of the Dumlu region generally have a "saline-alkali" soil characteristic, making them heavier in texture compared to normal soil, with very high electrical conductivity and rich in lime, Na, Ca and Mg.

Based on initial soil analyzes, ammonium sulfate (20.5% N) and triple superphosphate (48% P_2O_5) fertilizers were applied as a standard basal fertilizer at a rate of 10 kg N/da and 5 kg P_2O_5 /da for *Puccinellia distans* to ensure optimal plant development. SiO_2 (0, 1, 2, and 4 mM) and KNO_3 (0, 20, and 40 mM) applications were applied to pots along with seed sowing. Following fertilizer application, 40 seeds

Table 1. Ec, Ph, CEC values of soil samples

Soil type	pH	Ec (dS/m)	Ca (me 100g ⁻¹)	K (me 100g ⁻¹)	Mg (me 100g ⁻¹)	Na (me 100g ⁻¹)
1	7.91	1000	1.76	0.25	1.17	14.50
2	8.94	8060	1.45	0.49	0.65	22.14
3	8.79	8527	1.69	0.70	0.78	23.36
4	8.86	4480	0.47	1.00	0.52	22.95

of *Puccinella distans* were sown per pot at a rate of 1 kg per decare. The soil samples with plant emergence (soil samples 1 and 2) were thinned after germination, leaving 20 plants in each pot.

During the plants' growth period, their water needs were met with normal irrigation water, and the soil moisture level was attempted to be maintained at 50% of field capacity. The temperature and humidity values of the greenhouse conditions throughout the day were measured using a data logger (Testo 175-H2 V01.10), and approximate irrigation intervals were determined by weight calculation. The number of main stems, plant height, number of leaves, fresh forage yield and dry matter yield, and crude protein, ADF, and NDF analyzes were performed on the plants harvested from the pots where each treatment was applied. The data obtained from the research results were subjected to variance analysis using the JMP 5.1 statistical software package, and the significant means were compared according to the LSD test.

3. Results and Discussion

3.1. Plant height

According to the research results, the effects of the applied treatments were found to be significant on the soil types used and between years ($p < 0.01$). In addition, the soil type \times application interaction (ST \times A) was significant (Table 2 and 3). In the second year, a decrease in plant height was observed compared to the first year. A 35% reduction was observed in saline-alkali soil compared to normal soil (Table 2). Among

the applications, the highest value (17.50 cm) was obtained from the S₁K₂ application compared to the control group (14.33 cm) (Table 2). Aridity and high salt accumulation have reduced plant height. Studies have shown that salt stress reduces growth parameters such as root and shoot length, plant height, leaf area, and biomass accumulation (Parihar et al., 2015; Ahmed et al., 2022; Balasubramaniam et al., 2023). In addition, it is known that the combined application of silicon and potassium enhances plant growth by reducing Na accumulation and ESP (exchangeable sodium percentage), and increasing the K/Na ratio, especially under stress conditions (Zargar et al., 2019; Ghazi et al., 2021).

3.2. Number of main branch

The number of main branch in *Puccinella distans* was found to be 2.61 in normal soil and 2.32 in plants grown in saline-alkali soil (Table 2). This difference was determined to be statistically insignificant ($p > 0.05$). This situation may be due to the osmotic stress caused by salt stress leading to a decrease in plant growth rate (Ouertani et al., 2021; Kınay & Erdem 2022). The ST \times A interaction was statistically significant ($p < 0.05$) with the applied treatments ($p < 0.01$). Among the applications, the highest main branch number was found in the S₂K₁ and S₃K₁ applications, with a value of 3.25. Similarly, in a study conducted, it was found that silicon and potassium applications improved growth parameters such as the number of branch, number of seeds, seed yield, and plant height (Çakır, 2020).

Table 2. Plant height (cm), mean branch number, leaf number, ADF (%), NDF (%), crude protein ratio (%), crude protein yield (g), fresh forage yield (g/pot), and dry matter yield (g/pot) of *Puccinella distans* grown under different soil and different doses of silicon and potassium applications

Treatments		Plant height (cm)	Main branch number	Leaf number	ADF (%)	NDF (%)	Crude protein ratio (%)	Crude protein yield (g)	Fresh forage yield (g/pot)	Dry matter yield (g/pot)
Year	2009	14.56 ^a	2.58	5.79	32.84 ^a	44.96	11.34 ^b	19.15	5.80	1.69
	2010	14.10 ^b	2.35	5.61	32.49 ^b	44.14	11.82 ^a	20.64	6.04	1.75
	Mean	14.33	2.47	5.70	32.67	44.55	11.58	19.90	5.92	1.72
Soil Type	1	17.40 ^a	2.61	5.53	32.66	44.95	10.87 ^b	20.36	6.17 ^a	1.87 ^a
	2	11.21 ^b	2.32	5.88	32.66	44.14	12.28 ^a	19.44	5.67 ^b	1.56 ^b
	Mean	14.31	2.47	5.70	32.66	44.55	11.56	19.90	5.92	1.72
Application	S ₀ K ₀	14.33 ^{cd}	2.08 ^{df}	5.08 ^{cd}	32.06 ^{bd}	46.16 ^a	12.13 ^{ab}	17.07 ^{df}	5.35 ^{cd}	1.41 ^d
	S ₀ K ₁	16.17 ^{ab}	1.50 ^f	3.50 ^e	31.88 ^d	43.64 ^{cd}	11.74 ^b	20.15 ^{bd}	6.21 ^{ac}	1.75 ^{ac}
	S ₀ K ₂	16.83 ^{ab}	2.00 ^{df}	4.75 ^{de}	32.94 ^a	44.86 ^{ac}	12.96 ^a	25.75 ^a	7.15 ^a	2.03 ^a
	S ₁ K ₀	13.92 ^{de}	1.92 ^{ef}	4.58 ^{de}	33.06 ^a	45.72 ^{ab}	12.11 ^{ab}	17.89 ^{df}	5.13 ^d	1.48 ^{cd}
	S ₁ K ₁	16.00 ^b	2.17 ^{de}	5.25 ^{cd}	31.95 ^{cd}	44.99 ^{ac}	12.35 ^{ab}	19.54 ^{ce}	5.76 ^{bd}	1.60 ^{bd}
	S ₁ K ₂	17.50 ^a	2.42 ^{ce}	5.83 ^{bd}	33.15 ^a	44.76 ^{bc}	12.45 ^{ab}	25.03 ^a	7.17 ^a	2.02 ^a
	S ₂ K ₀	13.00 ^{df}	2.33 ^{de}	6.33 ^{bc}	32.74 ^{ab}	44.92 ^{ac}	12.36 ^{ab}	22.06 ^{ac}	4.83 ^d	1.81 ^{ab}
	S ₂ K ₁	13.58 ^d	3.25 ^a	7.83 ^a	32.18 ^{bd}	44.06 ^c	10.31 ^c	18.43 ^{ce}	5.75 ^{bd}	1.76 ^{ac}
	S ₂ K ₂	12.50 ^{ef}	3.00 ^{ac}	5.33 ^{cd}	33.15 ^a	42.54 ^d	10.19 ^c	16.37 ^{ef}	6.51 ^{ab}	1.61 ^{bd}
	S ₃ K ₀	10.50 ^g	2.58 ^{bd}	6.08 ^{bc}	33.12 ^a	44.43 ^{bc}	10.00 ^c	14.38 ^f	5.28 ^{cd}	1.46 ^d
	S ₃ K ₁	15.50 ^{bc}	3.25 ^a	7.08 ^{ab}	32.66 ^{ac}	44.62 ^{bc}	11.78 ^b	23.51 ^{ab}	6.35 ^{ac}	2.00 ^a
	S ₃ K ₂	11.83 ^{fg}	3.08 ^{ab}	6.75 ^{ab}	33.14 ^a	43.84 ^{cd}	10.54 ^c	18.58 ^{ce}	5.89 ^{bd}	1.76 ^{ac}
	Mean	14.31	2.47	5.70	32.67	44.55	11.58	19.90	5.95	1.72

Table 3. Analysis of variance (ANOVA) for plant height, number of main branches, leaf number, ADF (%), NDF (%), crude protein content (%), crude protein yield (g), fresh forage yield (g/pot) and dry matter yield (g/pot) of *Puccinella distans* as affected by year (Y), soil type (ST) and application (A) of silicon and potassium

Sources of variation	DF	Plant height (cm)	Main branch number	Leaf number	ADF (%)	NDF (%)	Crude protein ratio (%)	Crude protein yield (g)	Fresh forage yield (g/pot)	Dry matter yield (g/pot)
Years (Y)	1	**	ns	ns	**	ns	*	ns	ns	ns
Soil type (ST)	1	**	ns	ns	ns	ns	**	ns	*	**
Application (A)	11	**	**	**	**	**	**	**	**	**
Y×ST	11	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y×A	11	ns	ns	ns	ns	ns	ns	ns	ns	ns
ST×A	11	**	*	**	**	**	**	**	**	**
Y×ST×A	11	ns	ns	ns	ns	ns	ns	ns	ns	ns

* $p < 0.05$; ** $p < 0.01$; ns: not significant.

3.3. Number of leaf

The applications on the number of leaf and the ST×A interaction were significant ($p < 0.01$) (Table 2 and Table 3). Among the applications made, the S2K1 application resulted in the highest leaf count value, increasing by 54% compared to the control (7.83) (Table 2). The osmotic effect of salt stress indicates itself in plants thru reduced growth rates, changes in leaf color, alterations in the root/shoot ratio, and changes in the speed of plant maturation, while the ionic effect of salt stress is primarily seen thru damage to meristematic tissues or leaves (Ouertani et al., 2021). The application of silicon and potassium to plants has been adopted as an effective method because it alleviates the negative effects of stress and increases stress tolerance (Zhu & Gong, 2014; Walsh & Walsh, 2020). Similar to our study, Maghsoudi et al. (2019), Yıldırım and Güneş (2021), and Walsh and Walsh (2020) reported that the applied silicon and potassium improved the adverse conditions caused by stress in the plant's growth parameters.

3.4. Fresh forage yield

Soil type was found to be 5% significant for fresh forage yield, while the interaction between applications and ST×A was determined to be significant ($p < 0.01$) (Table 2 and 3). The fresh forage yield, determined as 6.17 g/pot in normal soil, decreased to 5.67 g/pot in saline-alkali soil. Over the years, fresh forage yield, which was 5.80 g/pot in the first year, was determined to be 6.04 in the second year, but this increase was found to be statistically insignificant. Among the applications performed, an increase was generally determined compared to the control, while the S₁K₂ application provided the highest increase in dry matter yield (7.17 g/pot) (Table 2). Kınay and Erdem (2022) observed decreases in the fresh forage yield and dry matter yield under increasing salt applications. However, similar to our study, it was determined that these decreases were reduced with silicon applications. This situation may have resulted from the application of silicon, which increased the plant's salt tolerance by reducing Na concentrations and increasing K concentrations. Indeed, silicon (Si) is known to promote plant growth and improve

plant biomass and productivity under various stress conditions (Deshmukh et al., 2017). In addition to this, potassium plays an important role in maintaining the water content of plant tissues, as well as in the basic physiological functions of plants such as protein synthesis and the production of sugars and starches (Pandey & Mahiwal, 2020).

3.5. Dry matter yield

According to the research results, the effects of soil type, applied practices, and the interaction of ST×A on the dry matter yield of *Puccinellia distans* were found to be statistically significant ($p < 0.01$) (Table 2 and 3). The dry matter yield increased depending on the applications and the fertilizer doses applied. The highest dry matter yield was obtained from the application of 40 mM potassium without silicon (S₀K₂, 2.03 g/pot) (Table 2). Growth reduction is a common symptom of any plant under high salinity stress due to disrupted ionic balance (Kundu et al., 2018). In the study conducted, it was also determined that salinity stress negatively affects plant growth and development (El Sabagh et al., 2021).

Potassium is a macronutrient essential for physiological processes in plants, such as enzyme activation, regulation of osmotic pressure, and stomatal movement (Wang et al., 2013).

It is also known that increasing potassium and calcium concentrations in plants under salt stress can improve the plant's osmoregulatory adaptation to salt stress, thereby mitigating the harmful effects of salinity on growth and yield (Nelson, 1978). Ju et al. (2021) and Hafeez et al. (2024), similar to our study, stated that potassium application has positive effects on salinity and mitigates the negative effects of salinity on wheat seedlings.

3.6. Crude protein ratio

The effect of soil type, applications, and the ST×A interaction on crude protein content was determined to be statistically significant ($p < 0.01$) (Table 2 and 3). Additionally, the difference between the years has been significant ($p < 0.05$). The highest crude protein ratio, at 12.96%, was obtained from the 40 mM potassium

application (S_0K_2) without silicon. The crude protein ratio, which was 11.34% in the first year, increased to 11.82% in the second year (Table 2). The crude protein ratio was found to be 10.87% in normal soil and 12.28% in saline soil. Generally, it has been reported that salinity reduces the crude protein (CP) ratio in forage crops however, the study determined that salinity did not affect the protein content in canola (Francois, 1994).

Additionally, another study found that potassium silicate application increased carbohydrate and protein ratio in plants (Hellal et al., 2020). This situation could be a result of potassium silicate's role in increasing the transport of nutrients essential for protein and carbohydrate biosynthesis in plants, which is facilitated by its enhancement of the photosynthetic process.

3.7. Crude protein yield

According to the research results, the crude protein yield was found to be statistically significant for the applied treatments and the $ST \times A$ interaction ($p < 0.01$) (Table 2 and 3). The crude protein yield in the second year increased compared to the first year and was determined to be statistically insignificant. The crude protein yield in saline-alkali soil, which was 19.44 g, was 20.36 g in normal soil. Because the high salt concentration reaches a threshold that inhibits nutrient uptake and plant growth (Wang et al., 2023; Abebe & Tu, 2024). The highest crude protein yield of 25.75 g was obtained from the S_0K_2 application (Table 2). Indeed, in their study, Walsh and Walsh (2020) reported that potassium can contribute to protein synthesis by increasing the nitrogen content in wheat.

3.8. ADF ratio

The change in the ADF ratio was found to be significant across years and applications ($p < 0.01$). Additionally, the $ST \times A$ interaction was found to be statistically significant. The ADF ratio decreased in the second year compared to the first year (Table 2 and 3). The S_0K_1 (31.88%) and S_1K_1 (31.95%) applications caused a decrease in ADF ratio compared to the control (Table 2). Salinity and alkalinity stress can cause changes in the crude protein and fiber content of forage crops, leading to reduced nutrient uptake and impaired metabolic processes, which can decrease their nutritional value. The applications performed have improved the digestibility of the plant by reducing the ADF ratio. The results obtained approached the desired ADF ratio for forage crops (31%) (Attia-Ismail, 2015) and varied between 31 and 33 %.

3.9. NDF ratio

The effect of applications on the NDF ratio was found to be significant ($p < 0.01$). Additionally, the $ST \times A$ interaction was statistically significant (Table 2 and 3). All the applications performed reduced the NDF ratio compared to the control (46.16%). The applications were evaluated positively as reducing the NDF ratio in the rumen leads to better digestibility and energy efficiency. Indeed, in forage

crops, it is desirable for the NDF content to be below the upper limit of 40% in terms of quality (Attia-Ismail, 2015).

4. Conclusion

In this study, the effects of different doses of silicon and potassium fertilizers on the yield and yield components of the halophyte plant *Puccinellia distans*, adapted to regional conditions, were investigated in terms of bringing saline-alkali areas into production. According to our results, growth parameters such as plant height, leaf number, fresh forage yield and dry matter yield showed a decrease in saline-alkali soil, while silicon and potassium applications significantly reduced these negative effects. Especially the S_1K_2 and S_0K_2 applications provided the highest values in terms of growth and yield. The crude protein content and yield were also positively affected by the applications, with the highest value determined in the silicon-free application at a potassium dose of 40 mM (S_0K_2). When evaluated in terms of feed quality, the ADF and NDF ratios were reduced thru the applications, which was positively evaluated in terms of the plant's digestibility. In conclusion, silicon and potassium applications have been effective in improving the growth, yield, and quality parameters of *Puccinellia distans*, especially under saline-alkali soil conditions. These findings make significant contributions to the sustainability of agricultural production in these areas.

Acknowledgement

The first-year results of the study were presented in abstract form at a congress. The study was supported financially by Atatürk University Scientific Research Projects Coordination Unit (BAP 2009/27).

Conflict of interest

The authors declare no conflict of interest.

Ethical Approval

This article does not require ethics committee approval.

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