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Mitigating Salt Stress in Cool-Season Turfgrasses Using Nano Silicon and Humic Acid: A Comparative Evaluation on *Festuca arundinacea* and *Lolium perenne*

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Abstract

Salinity stress is one of the major abiotic constraints limiting turfgrass growth, visual quality, and sustainability in landscape areas, particularly in regions where secondary-quality irrigation water is increasingly used. Developing effective and environmentally friendly management strategies to mitigate salinity-induced damage has therefore become a critical challenge for turfgrass systems. This study evaluated the effectiveness of nano silicon and humic acid in mitigating salinity stress in *Festuca arundinacea* 'Bizem' and *Lolium perenne* 'Ringles' grown under 6 dS m^{-1} NaCl conditions. Salinity significantly reduced turfgrass quality, color, chlorophyll content, and growth parameters in both species. Nano silicon applications, especially at 200 cc da^{-1} (NS200), markedly alleviated salinity-induced damage. Compared with the salt-stressed control, NS200 increased chlorophyll content by 51.4–62.6%, turfgrass quality scores by 25.1–31.2%, weekly clipping dry weight by 165.1-232.4**%** across both species. In contrast, humic acid applied at 300 cc da^{-1} showed limited improvements under the same salinity level. Overall, the results demonstrate that nano silicon, particularly at 200 cc da^{-1}, provides a more effective and consistent strategy than humic acid for improving physiological performance and visual quality of cool-season turfgrasses under moderate salinity stress.

Keywords Turfgrass management · Landscape maintenance · Abiotic stress · Nanotechnology · Organic fertilizer

Introduction

Global warming has intensified climate change–related problems such as drought, desertification, and water scarcity, leading to increasing pressure on limited water resources. Rising temperatures and uncontrolled water use have reduced both the quantity and quality of available water, particularly in arid and semi-arid regions. As a result, demand for water continues to increase across agricultural and landscape systems. In landscape areas such as parks, gardens, and turfgrass surfaces, irrigation requirements can be substantial, prompting the development of water-efficient landscaping approaches aimed at reducing water consumption. In this context, the use of secondary-quality irrigation water has become increasingly common in both agricultural and landscape applications (du Jardin 2015; Yakhin et al. 2017; Rouphael and Colla 2020; OECD 2017). However, secondary-quality waters often contain elevated salt levels, and salinity in soil or irrigation water represents a major environmental constraint that negatively affects plant

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growth, quality, and long-term performance, particularly in turfgrass species with generally low salt tolerance (Carrow and Duncan 1998; Kozłowska et al. 2021).

Humic substances are widely recognized biostimulants that contribute to the mitigation of abiotic and biotic stresses in plants (du Jardin 2015; Yakhin et al. 2017). These naturally occurring, heterogeneous organic compounds are known to enhance plant growth by regulating primary and secondary metabolism and improving tolerance to abiotic stress conditions, including salinity (Jindo et al. 2020; Shah et al. 2018; Canellas et al. 2015; Canellas and Olivares 2014). Numerous studies have reported that humic acid applications can alleviate salinity-induced stress by improving physiological and growth-related parameters in various plant species (Çimrin et al. 2010; Jarosova et al. 2016; Rady et al. 2016; Mazhar et al. 2012). In turfgrasses, humic acid has been shown to enhance chlorophyll content, visual quality, nutrient uptake, and biomass production under saline conditions (Maibodi et al. 2015; Saeedi Pooya et al. 2018; Sharifiasl et al. 2019; Zhu and Li 2018). However, the magnitude of these responses has been reported to vary considerably depending on application dose, method, turfgrass species, and salinity level.

Silicon (Si) is one of the substances considered beneficial for plant life (Luyckx et al. 2017; Coskun et al. 2019; Karimi and Mohsenzadeh 2016). Si can be found in different fractions in the soil as liquid, solid or adsorbed. The liquid and adsorbed phases of Si are plant-available forms because they contain orthosilicic acid (H_4SiO_4), which is the main form of silicon in soil (Seleiman et al. 2019). Several studies have reported that externally applied silicon fertilization contributes to the development of stronger root tissues, enhanced antioxidant enzyme activity, and improved regulation of cellular water balance (Siddiqui et al. 2014; Coskun et al. 2019; Bhat et al. 2021; Ahmadi-Nouraldinvand et al. 2023). Si can increase plant growth and development as well as plant resistance due to the promotion of phosphorus utilization. There are many studies showing that Si fertilization increases plant productivity especially under salt stress (Torabi et al. 2015; Saleh et al. 2018). There are also studies supporting that different silicon sources mitigate the negative effects of stress in grass plants exposed to salt stress (Esmaeili et al. 2015; Çakır 2020). It is stated that silicon in the form of nano silicon with smaller particle size produced with new technology shows more effect than standard silicon sources when sprayed on the leaf surface, thus being more effective in alleviating stress factors (Bhat et al. 2021; Wang et al. 2015; Çakır 2020). In the literature, there are few studies investigating the effects of nano silicon in turfgrasses under salinity stress. Chai and Shao, (2010) applied different doses of silicon in *Poa pratensis* seedlings under salinity stress and determined that silicon application may contribute to better grass quality and growth under saline conditions. Taher et al. (2023) applied silicon to *Paspalum vaginatum* and Tifway Hybrid Bermuda grass (*Cynodon transvaalensis* × *C. dactylon*), which are frequently used in golf and football fields, under cold and salt stress, showed that humic acid, ferrous sulfate, different silicon sources (silica, diatomite) applied at different doses improved the growth of both species compared to the control in terms of all the parameters considered, and a greater improvement was observed when iron sulfate and humic acid were used compared to silicon. Rahimi et al. (2021) investigated the efficacy of two different clinoptilolite zeolites, a silicon-rich mineral, to mitigate the negative effects of salt in *Lolium perenne* under salinity stress. In their study, it was determined that under salt stress, both zeolite treatments significantly reduced Na content in shoots by 44.36% and 21.31%, but increased K content by 272.34% and 81.59%, and also increased the K/Na ratio by 590.47% and 129.43%, respectively. Thus, it was concluded that both forms of zeolite, a Si-rich mineral, partially reduced the negative effects of salinity on perennial ryegrasses. Recent studies have demonstrated that silicon nanoparticles can significantly enhance salinity tolerance by activating antioxidant defense systems, improving ionic balance, and stabilizing physiological processes in cereal species such as wheat and rye (Ahmadi-Nouraldinvand et al. 2023; Narimani et al. 2025).

Although numerous studies have investigated the effects of silicon or humic substances on plant tolerance to salinity, most of this research has focused on conventional silicon sources such as silicates or bulk silicon fertilizers. Comparative evaluations of nano silicon and humic acid applications under controlled salinity conditions in cool-season turfgrass species therefore remain limited. Due to its nano-scale particle size, higher surface area, and enhanced bioavailability, nano silicon may facilitate more efficient foliar absorption and improved physiological responses under stress conditions. In this context, the present study provides a comparative evaluation of nano silicon and humic acid applications at different doses in two widely used cool-season turfgrass species, *Festuca arundinacea* and *Lolium perenne*, under defined salinity stress conditions. By integrating visual quality traits with physiological and growth-related parameters, this study aims to evaluate the effectiveness of nano silicon and humic acid applications and to determine appropriate nano silicon application rates for mitigating salinity stress in turfgrass management.

Materials and Methods

The main material of the study was *Lolium perenne* "Ringles" and *Festuca arundinacea* "Bizem" varieties of cool climate grasses. Certified seeds of *Lolium perenne* 'Ringles'

and *Festuca arundinacea* 'Bizem' were obtained from Fito Tohum (Türkiye). The seeds were supplied as commercial turfgrass cultivars commonly used in landscape applications and were used without any pre-treatment prior to sowing. Both species are the most commonly used cool climate grass species for overseeding on warm climate grass species in parks and gardens, sports fields, highway median strips and other lawn areas for different purposes.

Planning of the Trial and General Maintenance Practices

The experiment was established on 30.11.2021 in the glass greenhouse located in Akdeniz University Landscape Architecture Ornamental Plants Research and Application Field. The greenhouse conditions used in this study (25/20°C day/night temperature, 14-h photoperiod, and a minimum photosynthetically active radiation (PAR) level of 400 µmol m^{-2} s^{-1}) were selected based on commonly applied controlled-environment settings for cool-season turfgrass species reported in previous studies (Beard 1973; Fry and Huang 2004; Kang et al. 2013; Rouphael and Colla 2020). Plastic pots with a diameter of 18 cm and a height of 16 cm (3 L) were used. Sterilized sand, sterile peat and perlite were prepared in a ratio of 5:4:1. A total of 5.5 kg of growing medium was placed in each pot. As a result of the calculation of the amount required for 1 square meter of each grass species according to the size of the pots, the amount of seed per pot was calculated considering the average amount of seed recommended in the literature (Jovanovic Todorovic et al. 2020; Hare et al. 1990); *L.perenne* was sown at 35 g/m^2 and *F. arundinace* at 45 g/m^2 and cover soil was sprinkled on the pots at a maximum of 2 times (approximately 1-1.5 times) the seed. Pots were irrigated regularly and equally at field capacity (Table 3.1). The experiment was arranged as a completely randomized factorial design with three factors: turfgrass species (2 levels: *F. arundinacea* and *L. perenne*), salinity (2 levels: Salt−; 0 dS m^{-1} NaCl; and Salt+; 6 dS m^{-1} NaCl), and biostimulant treatment (4 levels: Control (no biostimulant), NS100 (nano silicon at 100 cc da^{-1}), NS200 (nano silicon at 200 cc da^{-1}), and HA300 (humic acid at 300 cc da^{-1}). This resulted in a total of 16 treatment combinations (2 × 2 × 4), each replicated three times. Each pot was considered the experimental unit. In total, 48 pots were used in the experiment. Biostimulant treatments were coded as Control, NS100, NS200, and HA300, and combined with two salinity levels (Salt − and Salt+). A schematic representation of the factorial experimental design, replication structure, and treatment codes is provided in Fig. 1. After sowing the seeds, irrigation was regularly applied to each pot at two-day intervals at equal field capacity. In order to encourage the tillering of the grass growing in the pots, mowing was applied 4 cm from the soil surface. Mowing started 15 days after seed sowing and continued regularly every week, once a week. The first fertilization was applied 1 month after sowing. 18-18-18 (N-P-K) compound fertilizer was applied

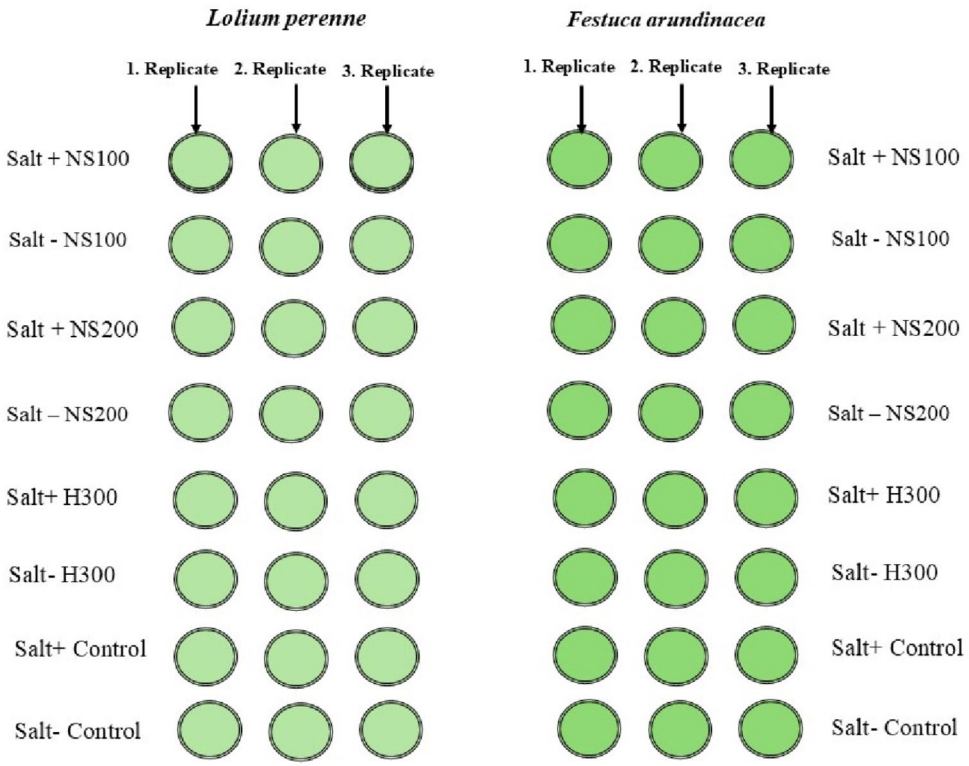


Fig. 1 Schematic representation of the 2 × 2 × 4 factorial experimental design showing turfgrass species (*L. perenne* and *F. arundinacea*), salinity levels (Salt − and Salt+), biostimulant treatments (Control, NS100, NS200, and HA300), and replication structure. Each circle represents one pot, which was considered the experimental unit

every two weeks at a rate of 2.5 g of pure nitrogen per m^2, 0.31 g per pot. Saline water application was started by first determining the amount of water needed by the plant. Salt water was obtained by adding NaCl in the total amount of water to be given. The salt concentration of the obtained saline water was measured and the desired concentration was obtained.

Saline, Nano Silicon and Humic Acid Applications

Saline water was first applied 14 weeks after seed sowing. To avoid acute salt toxicity, salinity was gradually increased over one week from 1 dS m^{-1} to the target level of 6 dS m^{-1}. Thereafter, all saline irrigation treatments were maintained at an electrical conductivity of 6 dS m^{-1} until the end of the experiment. This salinity level was selected based on previous studies identifying 6 dS m^{-1} as a critical threshold for cool-season turfgrass species, at which growth reduction and visual quality decline become evident (Harivandi et al. 1992; Marcum and Pessarakli 2006). In addition, this level represents moderate salinity conditions commonly encountered in turfgrass systems irrigated with secondary-quality or reclaimed water, particularly in arid and semi-arid regions.

"Eckosil" (Unittar-Asfestglobal) was used as the nano-silicon source. According to the manufacturer, Eckosil contains SiO_2 nanoparticles supplemented with 1.2% (w/w) water-soluble iron, 0.0035% (w/w) water-soluble molybdenum, 1% water-soluble zinc, and 5.4% ortho-ortho silicic acid. Nano-silicon was applied at two application doses: 0 (control), 100, and 200 cc per decare, based on the manufacturer's recommended rate of 100 cc per decare. The corresponding amounts were applied to each plant by foliar spraying using 200 mL of water. Since the nano silicon solution was prepared with distilled water, 200 ml of distilled water was applied by foliar spraying to the pots that were not given nano silicon in order not to disturb the experimental conditions. Nano silicon application was first started on 22.02.2022, about 4 weeks before the salt stress started, and it was repeated once more on 04.04.2022 (about 3 weeks after the salt stress started), and it was applied twice in total. "Blackjack SC" (Altıntar Agriculture) was used as humic acid in the experiment. "Blackjack" contains 15% total organic matter, 15% total humic and fulvic acid and 0.03% water soluble potassium oxide. In humic acid application, two doses of 0 and 300 cc per decare were applied. Humic acid was applied as a foliar spray at a dose of 300 cc da^{-1}. The calculated amount of humic acid solution was sprayed uniformly onto the leaf surface of each pot. No soil or root-zone application of humic acid was performed during the experiment. Humic acid application was first started on 22.02.2022, about 4 weeks before the salt stress started, and it was repeated once more on 04.04.2022 (about 3 weeks after the salt stress started), and it was applied twice in total. Humic acid was evaluated at a single application rate (300 cc da^{-1}), which corresponds to the standard field-recommended dose provided by the manufacturer and commonly used in turfgrass management practices. In contrast, nano silicon was tested at two application rates (100 and 200 cc da^{-1}) to allow a dose-response evaluation, as information on optimal nano silicon doses for cool-season turfgrass species under salinity stress is still limited. The primary objective of this study was not to establish a full dose–response curve for humic acid, but rather to compare the relative effectiveness of a commonly applied humic acid dose with different nano silicon application rates under identical salinity conditions.

Observations Taken During the Experiment

Leaf firing (%), turfgrass quality and root-shoot growth measurements have been reported to be the best criteria for determining tolerance to salinity in turfgrasses (Marcum and Kopec 1997; Marcum et al. 2005; Marcum and Pessarakli 2006; Kozłowska et al. 2021; Taher et al. 2023). Throughout the experiment, turf color, turfgrass quality, leaf firing (%), weekly amount of clippings (wet and dry weights) and chlorophyll content were determined weekly. At the end of the experiment, wet and dry weights of shoots and roots were measured. Turf color; both the color obtained during the active growing season and the ability to maintain its color in autumn and winter months and under stress is not the genetic color of the plant, but the color of the plot as a whole. It was visually assessed using a 1–9 color scale. On this scale, a value of 1.0 indicates complete yellowing, 6.0 indicates light green and 9.0 indicates dark green color. Data were taken once a week. Turfgrass quality; is a combination of color, density, texture and response to stresses (Turgeon 1999). It was visually assessed using a 1–9 quality rating scale. In these evaluations, taking into account the components of the grass such as color, homogeneity, number of shoots per unit area and appearance, a value of 1.0 indicates complete yellowing (dormancy or death), 6.0 indicates minimum acceptable quality, and 9.0 indicates ideal shoot density, texture, color, homogeneity and excellent or ideal quality. Data were taken once a week. Wet and dry weights of mowing residues: The pots were mowed weekly at 4 cm and the crop residues were immediately weighed in the laboratory on a precision balance to determine wet weights. The crop residues were dried in an oven at 72 °C for 48 h, weighed and dry weights were determined. Chlorophyll content; was measured from each pot once a week during the period when the plants were exposed to salt spray using a chlorophyll meter (Fieldscout CM 1000). The chlorophyll meter was held conically from the top of the pots at

a distance of 30–183 cm and ten measurements were taken from each pot. The specified chlorophyll meter measures the relative chlorophyll content using 700 nm and 840 nm wavelength light reflected from the grass canopy. Shoot and root wet and dry weights: Compared to control plants, the change in shoot and root dry weights in plants irrigated with saline irrigation water is one of the most important measures used as an indicator of salinity tolerance (Maas 1990). At the end of the experiment, the plants were carefully removed from the pots together with the soil and all the shoots and roots were harvested by separating them from the root crown that brought them together. The shoots and roots were carefully washed to remove all soil and immediately weighed in paper envelopes and then dried at 72 °C for 48 h and dry weights were measured and weighed.

Data Analysis

Data were subjected to analysis of variance (ANOVA) using SPSS software (IBM, Armonk, NY, USA) version 17 in a completely randomized factorial design with three replications per treatment combination. Each pot was considered an experimental unit. The residual mean square from the ANOVA was used as the error term for testing treatment effects. Mean comparisons were performed using Duncan's multiple range test at the 5% significance level. In addition to statistical significance, treatment effects were interpreted based on the magnitude and consistency of differences among means to reflect biologically meaningful responses under salinity stress conditions.

Results

Overall, salinity stress significantly reduced visual performance parameters in both species; however, NS200 consistently mitigated these negative effects across species. Analysis of variance results revealed that species ($P \leq 0.001$), salt ($P \leq 0.001$) and treatments ($P \leq 0.001$) had significant effects on color values (Table 1). Color values also showed significant differences depending on species × treatment ($P \leq 0.001$), salt × treatment ($P \leq 0.001$) and species × salt × treatment interaction effects ($P \leq 0.01$) (Table 1). When the color values were examined at the main effects level, it is seen in Table 2 that *F. arundinacea* species had a mean of 7.01 and *L. perenne* species had a mean of 6.37. When salt was examined at the main effects level, it was found that the average color value decreased with 6 dS m^{-1} salt application (Table 2). When the treatment averages were analyzed, the highest value with a statistical difference was found in the grasses with NS200 application with a value of 7.59, followed by NS100 application (6.87), H300 application (6.23) and control (6.06) (Table 2). As shown in Table 3, color values decreased under 6 dS m^{-1} salt application, with the strongest reductions observed in control and humic acid treatments, whereas NS200 largely maintained color scores. However, this decrease was not statistically significant in *L. perenne* species treated with NS200 and *F. arundinacea* species treated with NS100, indicating that the treatments helped to reduce the negative effect of salt (Table 3). In humic acid application, the decrease in color values with 6 dS m^{-1} salt application showed a statistically significant difference and was ineffective in mitigating the negative effect of salt in both species (Table 3). Representative visual differences among treatments under salinity stress are shown in Fig. 2, while the effects of biostimulant treatments on turf color ratings under salinity stress are shown in Fig. 3.

In line with the color responses, turfgrass quality ratings were also significantly affected by salinity and biostimulant treatments. As shown in Table 1, the effects of species ($P \leq 0.001$), salt ($P \leq 0.001$), treatment ($P \leq 0.001$) and salt × treatment interaction ($P \leq 0.001$) on quality were statistically significant. When the quality was analyzed in terms of species main effect, *F. arundinacea* was significantly higher than *L. perenne* (Table 2). In the context of the main effect of salt, it was determined that the average value decreased with 6 dS m^{-1} salt application (Table 2). When the biostimulant treatments were analyzed at the level of main effects, the

Table 1 Analysis of variance (mean squares) for color, quality, leaf firing, chlorophyll content, weekly clipping dry weight, root dry weight and shoot dry weight of *L. perenne* and *F. arundinacea* species evaluated for salt and treatments

Source of variation	Mean square							
	df	Color	Quality	Leaf firing	Chlorophyll content	Weekly clipping dry weight	Root dry weight	Shoot dry weight
Species (S)	1	4.851***	6.035***	476.784***	18427.138***	0.004*	25.946^{NS}	67.711**
Salt (SA)	1	6.206***	5.824***	751.134***	10646.35***	0.006**	5.116 ^{NS}	70.883***
Treatment (T)	3	5.851***	5.690***	763.859***	15097.315***	0.24***	1.292 ^{NS}	6.004 ^{NS}
SxSA	1	0.190 ^{NS}	0.97 ^{NS}	12.161 ^{NS}	145.464 ^{NS}	1.875 ^{NS}	1.119 ^{NS}	0.840 ^{NS}
SxT	3	0.722***	0.674***	90.396***	391.013 ^{NS}	0.002 ^{NS}	8.159 ^{NS}	0.346 ^{NS}
SAxT	3	0.374***	0.068 ^{NS}	72.058***	74.400 ^{NS}	0.001 ^{NS}	29.638*	5.622 ^{NS}
SxSAxT	3	0.231**	0.076 ^{NS}	9.456 ^{NS}	308.663 ^{NS}	0.000 ^{NS}	8.485 ^{NS}	1.657 ^{NS}
Error	32	0.50	0.072	4.656	176.488	0.001	8.738	5.680

NS, *, **, ***: Non significant and significant at $P \leq 0.05$, ≤ 0.01 and ≤ 0.001, respectively

Table 2 Mean comparisons for the effects of species, salt and treatments on color, quality, leaf firing, chlorophyll content, weekly clipping dry weight, root dry weight and shoot dry weight of *F. arundinacea* and *L. perenne*

Treatment factor	Observed parameters						
	Color	Quality	Leaf firing (%)	Chlorophyll content (SPAD)	Weekly clipping dry weight (g)	Root dry weight (g)	Shoot dry weight (g)
Species							
F. arundinacea	7.01 ± 0.41 a[x]	7.13 ± 0.39 a	14.29 ± 4.38 b	190.13 ± 23.2 a	0.09 ± 0.02 b	10.09 ± 1.88 a	13.33 ± 1.63 a
L. perenne	6.37 ± 0.50 b	6.42 ± 0.49 b	20.60 ± 5.88 a	150.94 ± 19.74 b	0.11 ± 0.02 a	8.62 ± 1.63 a	10.96 ± 1.26 b
Salt							
0 dS m^{-1}	7.05 ± 0.41 a	7.13 ± 0.45 a	13.49 ± 4.16 b	185.43 ± 23.35 a	0.11 ± 0.03 a	9.03 ± 1.76 a	13.36 ± 4.27 a
6 dS m^{-1}	6.33 ± 0.47 b	6.43 ± 0.44 b	21.40 ± 5.63 a	155.64 ± 22.25 b	0.09 ± 0.03 b	9.68 ± 1.84 a	10.93 ± 2.62 b
Treatments							
Control[y]	6.06 ± 0.50 c	6.08 ± 0.34 d	24.94 ± 5.75 a	136.35 ± 12.08 c	0.05 ± 0.01 d	9.65 ± 1.94 a	12.73 ± 1.61 a
NS100*	6.87 ± 0.25 b	6.99 ± 0.31 b	14.28 ± 2.68 c	187.98 ± 15.04 b	0.11 ± 0.02 b	9.40 ± 1.40 a	11.93 ± 0.99 a
NS200	7.59 ± 0.18 a	7.64 ± 0.28 a	7.68 ± 1.30 d	211.77 ± 19.67 a	0.15 ± 0.02 a	9.49 ± 1.83 a	12.68 ± 2.05 a
H300	6.23 ± 0.40 c	6.39 ± 0.47 c	22.87 ± 4.00 b	146.03 ± 19.17 c	0.07 ± 0.01 c	8.89 ± 2.13 a	11.24 ± 1.63 a

[x]In each column and treatment factor, means followed by the same letter are not significantly different at the 5% level according to Duncan's multiple range tests.

[y]Control; no biositimulant, NS100; nano silicon at 100 cc da^{-1}, NS200; nano silicon at 200 cc da^{-1}, H300; humic acid at 300 cc da^{-1}.

highest quality value was found in NS200 treatment (7.64), followed by NS100 (6.99), H300 (6.39) and control (6.08) treatments, respectively (Table 2). When the results were analyzed at the interaction level, it was observed that the mean quality values varied between 5.43 and 8.19 (Table 3). In terms of quality, it was determined that NS200 application reduced the negative effect of salt in both species, while there were no statistically significant differences in terms of 0 dS m^{-1} and 6 dS m^{-1} salt application (Table 3). Unlike *L. perenne*, similar results were observed in *F. arundinacea* species with NS100 application. The low dose of nano silicone applied to *F. arundinacea* also mitigated the negative effect of salt. In terms of quality values in both species, it was concluded that primarily nano silicon applications were useful in achieving the highest quality values. In humic acid application, both species showed a statistically significant difference with 6 dS m^{-1} salt application and the quality value decreased. The effects of nano silicon and humic acid applications on turfgrass quality under salinity stress are further illustrated in Fig. 3.

Leaf firing (%) increased significantly under salinity stress in both turfgrass species; however, NS200 reduced leaf damage compared with the salt-stressed control treatments. The effects of species ($P \leq 0.001$), salt ($P \leq 0.001$), treatment ($P \leq 0.001$) and species × treatment ($P \leq 0.001$) and salt × treatment ($P \leq 0.001$) binary interactions were statistically significant ($P \leq 0.001$) on leaf firing (%) (Table 1). When the main effects were analyzed in terms of species, it was observed that leaf firing (%) was lower in *F. arundinacea* (Table 2). When the results were analyzed in terms of the main effect of salt, it was found that 6 dS m^{-1} salt application increased the leaf firing (%) with a statistically significant difference (Table 2). At the main treatment level, the lowest leaf firing (%) was measured in NS200 treatment (7.68%), followed by NS100 (14.28%), H300 (22.87%) and control (24.94%) treatments with statistically significant differences (Table 2). At the interaction level, the lowest leaf firing (%) was found in *F. arundinacea* (5%) in NS200 treatment, 0 dS m^{-1} salt treatment, while the highest value was found in *L. perenne* (36.19%) in control treatment, 6 dS m^{-1} salt treatment (Table 3). It is seen in Table 3 that NS200 application mitigated the effect of salt on leaf firing (%) in *L. perenne* species and did not show a statistically significant difference with the control treatment, and this application helped to reduce the negative effects of salt stress. Graphical representation of leaf firing (%) responses to biostimulant treatments under saline conditions is presented in Fig. 4, highlighting the marked reduction in leaf damage under NS200 treatment compared with the salt-stressed control across both species.

Salinity stress resulted in a marked reduction in chlorophyll content in both species, whereas nano silicon applications, especially NS200, effectively preserved chlorophyll levels under saline conditions. The effects of different biostimulant applications applied to *F. arundinacea* and *L. perenne* species under salt stress during the trial period on chlorophyll contents were also determined. Table 1 shows that species ($P \leq 0.001$), salt ($P \leq 0.001$) and application ($P \leq 0.001$) effects are statistically significant, but their two- and three-way interactions are not significant. When the chlorophyll content is examined at the species main effect level, it is seen that *F. arundinacea* species has a higher

Table 3 Mean comparisons for the interaction effects of species, salt and treatments on color, quality, leaf firing, chlorophyll content, weekly clipping dry weight, root dry weight and shoot dry weight of *F. arundinacea* and *L. perenne*

Parameters	Species	Salt (dS m^{-1})	Treatments			
			Control[x]	NS100	NS200	H300
Color	*F. arundinacea*	0	7.34 ± 0.29 A[z] b[y]	7.14 ± 0.08 A b	8.09 ± 0.05 A a	7.14 ± 0.08 A b
		6	5.71 ± 0.16 B c	6.71 ± 0.25 A b	7.43 ± 0.08 B a	6.48 ± 0.05 B b
	L. perenne	0	6.00 ± 0.01 A b	7.24 ± 0.17 A a	7.48 ± 0.05 A a	5.95 ± 0.09 A b
		6	5.19 ± 0.10 B c	6.38 ± 0.13 B b	7.38 ± 0.09 A a	5.34 ± 0.05 B c
Quality	*F. arundinacea*	0	6.95 ± 0.05 A c	7.48 ± 0.09 A b	8.19 ± 0.17 A a	7.48 ± 0.05 A b
		6	6.05 ± 0.05 B b	6.72 ± 0.30 A b	7.57 ± 0.25 A a	6.62 ± 0.17 B b
	L. perenne	0	5.86 ± 0.14 A b	7.38 ± 0.05 A a	7.62 ± 0.05 A a	6.05 ± 0.17 A b
		6	5.48 ± 0.12 B c	6.38 ± 0.13 B b	7.19 ± 0.26 A a	5.43 ± 0.08 B c
Leaf firing (%)	*F. arundinacea*	0	10.24 ± 1.86 B b	9.76 ± 0.63 B b	5.00 ± 0.01 B c	14.33 ± 0.24 B a
		6	28.1 ± 0.63 A a	18.1 ± 2.81 A b	7.86 ± 0.41 A c	20.95 ± 1.26 A b
	L. perenne	0	25.24 ± 0.24 B a	11.43 ± 1.43 B b	7.86 ± 0.41 A c	24.05 ± 1.32 B a
		6	36.19 ± 1.33 A a	17.86 ± 1.09 A b	10.0 ± 1.65 A c	32.14 ± 1.09 A a
Chlorophyll Content (SPAD)	*F. arundinacea*	0	167.38 ± 8.32 A c	211.98 ± 1.02 A b	255.03 ± 8.44 A a	192.65 ± 2.77 A b
		6	131.21 ± 1.03 B b	198.27 ± 14.29 A a	213.32 ± 19.71 A a	151.18 ± 6.78B b
	L. perenne	0	131.13 ± 3.31 A b	189.26 ± 5.44 A a	203.60 ± 4.45 A a	132.39 ± 6.58 A b
		6	115.69 ± 0.70 B c	152.42 ± 5.97 B b	175.15 ± 2.99 B a	107.89 ± 1.94 B c
Weekly Clipping Dry Weight (g)	*F. arundinacea*	0	0.043 ± 0.01 A c	0.113 ± 0.01 A ab	0.147 ± 0.01 A a	0.093 ± 0.01 A b
		6	0.037 ± 0.01 A b	0.073 ± 0.01 A ab	0.123 ± 0.03 A a	0.070 ± 0.01 A ab
	L. perenne	0	0.057 ± 0.01 B b	0.150 ± 0.01 A a	0.173 ± 0.02 A a	0.083 ± 0.01 A b
		6	0.063 ± 0.01 A c	0.100 ± 0.01 B b	0.167 ± 0.01 A a	0.050 ± 0.01 B c
Root dry weight (g)	*F. arundinacea*	0	10.82 ± 2.72 A a	9.65 ± 1.69 A a	7.71 ± 0.04 B a	11.49 ± 2.64 A a
		6	8.18 ± 2.05 A a	9.69 ± 1.10 A a	13.58 ± 0.24 A a	9.62 ± 2.43 A a
	L. perenne	0	11.64 ± 0.24 A a	8.57 ± 1.87 A ab	6.75 ± 0.68 A b	5.62 ± 0.33 A b
		6	7.94±0.97 A a	9.71 ± 1.67 A a	9.93 ± 2.05 A a	8.83 ± 1.73 A a
Shoot Dry Weight (g)	*F. arundinacea*	0	15.43 ± 1.65 A a	12.88 ± 0.35 A a	15.87 ± 3.75 A a	13.47 ± 0.45 A a
		6	12.65 ± 1.29 A a	13.07 ± 1.49 A a	11.56 ± 0.47 A a	11.71 ± 0.30 A a
	L. perenne	0	13.44 ± 0.51 A a	11.51 ± 0.21 A a	12.96 ± 0.30 A a	11.31 ± 0.33 A a
		6	9.40 ± 0.45 B a	10.25 ± 0.60 A a	10.33 ± 0.47 B a	8.45 ± 2.63 A a

[x]Control; no biositimulant, NS100; nano silicon at 100 cc da^{-1}, NS200; nano silicon at 200 cc da^{-1}, H300; humic acid at 300 cc da^{-1}.

[z]Within each column and species, means followed by different upper case letters are significantly different by at the 5% level according to Duncan's multiple range test.

[y]Within each row means followed by different lower case letters are significantly different by at the 5% level according to Duncan's multiple range test.

average value (Table 2). When the salt is considered at the main effects level, it is determined that 6 dS m^{-1} salt application reduces the chlorophyll amount (Table 2). When the application means are examined, the highest chlorophyll rate was measured in NS200 application (211.77) with a statistically significant difference from the others, and this value was followed by NS100 (187.98) application. It is seen that there is no significant difference between H300 (146.03) and control (136.35) applications (Table 2). At the triple interaction level; in *F. arundinacea* species, the highest chlorophyll content was obtained in NS200 application in 0 dS m^{-1} salt application. While the chlorophyll content in the control group decreased significantly in 6 dS m^{-1} salt application, nano silicon applications significantly reduced this decrease. Table 3 demonstrates that NS200 consistently preserved chlorophyll content under saline conditions, whereas chlorophyll losses remained pronounced in control and humic acid treatments across both species. It is seen in Table 3 that the effect of humic acid application is statistically insignificant. In *L. perenne* species, the highest chlorophyll values were recorded in nano silicon applications. H300 application was insufficient to prevent the negative effects of salt and chlorophyll loss was observed in this application. In general, nano silicon applications were the most effective method in increasing chlorophyll content and protection against salt stress in both species.

The results for weekly clippings dry weight show that the effects of species ($P \leq 0.05$), salt ($P \leq 0.01$) and application ($P \leq 0.001$) are statistically significant (Table 1). When the main effect of salt on weekly clippings dry weight is examined, it is seen that the mean value which is 0.11 g in the control application decreases significantly to 0.09 g with 6 dS m^{-1} salt application. The analyses show that there are significant differences among the applications in terms of weekly



L. perenne
From left to right (1) Salt + NS100, (2) Salt + NS200, (3) Salt + H300, (4) Salt + Control



F. arundinacea
From left to right (1) Salt - Control, (2) Salt - NS100, (3) Salt - NS200, (4) Salt - H300



L. perenne
From left to right (1) Salt - Control, (2) Salt - NS100, (3) Salt - NS200, (4) Salt - H300



F. arundinacea
From left to right (1) Salt + NS100, (2) Salt + NS200, (3) Salt + H300, (4) Salt + Control

Fig. 2 Representative visual appearance of *L. perenne* and *F. arundinacea* grown under salinity stress (6 dS m^{-1} NaCl) and different biostimulant treatments after four weeks. From left to right: Salt+ NS100, Salt+ NS200, Salt+ HA300, and Salt+ Control for each species. Each pot represents one experimental unit

clippings dry weight and the plants applied with NS200 have the highest mean value (0.15 g) (Table 2). It is seen that this value is followed by the plants in the NS100 applied (0.11 g), H300 applied (0.07 g) and control (0.05 g) groups, respectively (Table 2). The highest value at the triple interaction level was determined in the *L. perenne* species that was applied NS200 without salt application, while it is seen in Table 3 that this value decreased with 6 dS m^{-1} salt application without any statistical difference. Similarly, the highest value was determined in the *F. arundinacea* species in the NS200 application without salt application. In addition, it was determined that the effects of 6 dS m^{-1} salt application in NS100 and NS200 applications in *F. arundinacea* species did not create a statistically significant difference compared to the 0 dS m^{-1} salt application (Table 3). This finding indicates that the negative effects of salinity were substantially mitigated in the specified species and treatments. Taken together, these results indicate that nano silicon application not only alleviated salinity-induced reductions but also sustained growth-related parameters at levels comparable to non-saline conditions as clearly reflected by the higher clipping dry weight values maintained under NS200 treatment compared with both control and humic acid applications.

It was determined that the double interaction effect of salt × application ($P \leq 0.05$) on root dry weight was statistically significant (Table 1). When the data were considered within the scope of the main effects of species, salt and application, it was seen in Table 2 that there was no statistically significant difference. When the data at the interaction level are considered, it is seen in Table 3 that the root dry weight values vary between 7.71 g and 13.58 g in *F. arundinacea* species and between 5.6 g and 11.64 g in *L. perenne* species.

As seen in Table 1, it was determined that the effects of species ($P \leq 0.01$) and salt ($P \leq 0.001$) on shoot dry weight were statistically significant, while the effects of the application and their two- and three-way interactions were not significant. When the shoot dry weight was examined within the scope of the species main effect, it was seen that *F. arundinacea* had significantly higher values than *L. perenne* (Table 2). When the salt main effect was evaluated, it was determined that there was a statistically significant decrease in shoot dry weight with the application of 6 dS m^{-1} salt

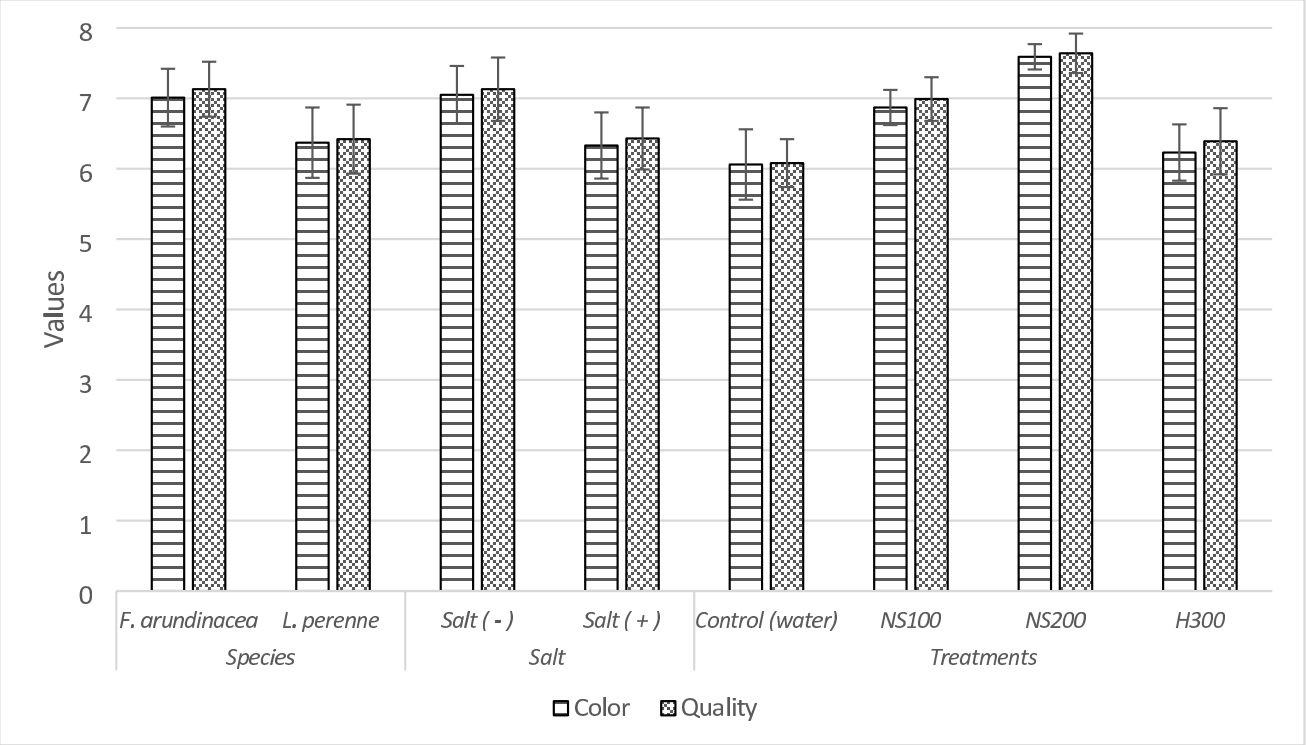


Fig. 3 Mean comparisons for the effects of species, salt and treatments on color, quality of *F. arundinacea* and *L. perenne*

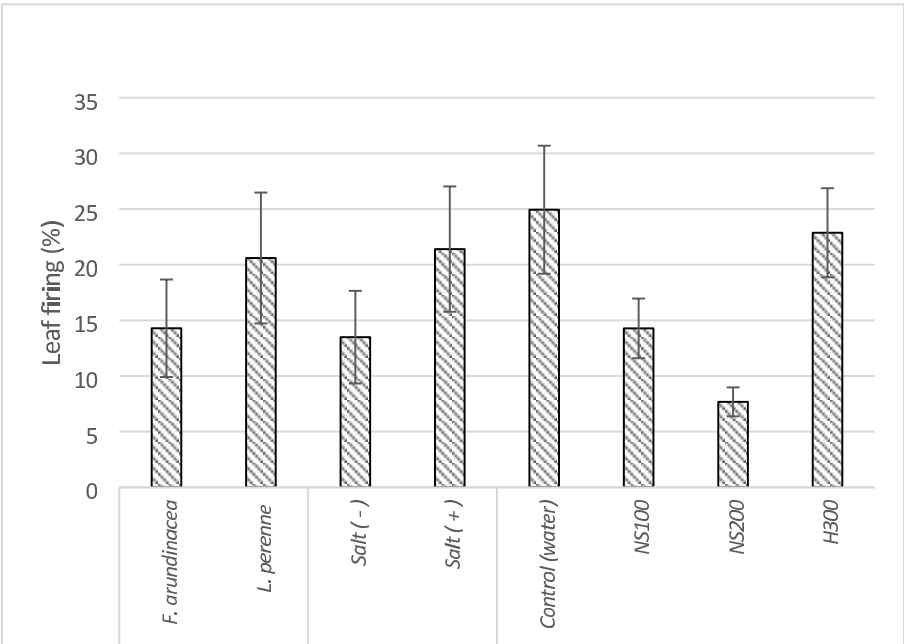


Fig. 4 Mean comparisons for the effects of species, salt and treatments on leaf firing of *F. arundinacea* and *L. perenne*

(Table 2). It was seen that no significant statistical differences emerged in terms of the application main effect, and the shoot dry weights varied between 11.24 g and 12.73 g (Table 2). When the data were examined at the interaction level, it was seen that the differences in shoot dry weights in *F. arundinacea* species in terms of 0 and 6 dS m^{-1} salt applications were not significant. In *L. perenne* species, 6 dS m^{-1} salt application decreased shoot dry weight; however, this decrease was partially limited by NS100 and H300 applications and did not show a statistically significant difference compared to the control group without salt application (Table 3). This situation shows that NS100 and H300 applications alleviated the negative effect of 6 dS m^{-1} salt

stress on shoot dry weight in *L. perenne* species and were effective in reducing biomass loss.

The results presented in this study showed that the negative effects of 6 dS m^{-1} salt on the examined parameters could be reduced in some applications carried out in *L. perenne* and F. *arundinacea* species. In *F. arundinacea* species, it was determined that NS100 application mitigated the negative effects of salt on color values, while NS200 application mitigated the negative effects of salt on quality, chlorophyll amount and root dry weight values. In *L. perenne* species, it was determined that NS200 application mitigated the negative effects of salt on color, quality, leaf firing and weekly cutting residual dry weight values. In the light of the findings obtained, it was concluded that nano silicon supplementation is a very suitable way to mitigate the negative effects of salt stress in the studied species. Research should be conducted to popularize the use of nano silicon in turfgrass management, to develop an effective management strategy to find affordable nano silicon sources and to develop methods to determine the conditions where nano silicon fertilization will be beneficial. It was determined that the effectiveness of H300 application was insufficient compared to nano silicon applications in both species in terms of color, quality, leaf firing (%) and chlorophyll content parameters. This situation is thought to be due to the insufficient dose of humic acid tested under the applied salinity level. In this context, studies investigating the effects of higher humic acid doses and different humic acid sources are needed.

Discussion

Salt stress is one of the main abiotic stress factors that has negative effects on growth parameters, physiological processes and visual quality in turfgrass species (Carrow and Duncan 1998; Kozłowska et al. 2021). In this study, the salt stress alleviation effects of nano silicon and humic acid applications on *F. arundinacea* and *L. perenne* species were evaluated. The findings showed that nano silicon applications were particularly effective in reducing the harmful effects of salt stress on many morphological and physiological parameters. Salt stress applied at 6 dS m^{-1} induced different stress responses between the two species. *F. arundinacea* maintained higher values for turf color, quality, chlorophyll content, and shoot dry weight, while exhibiting lower leaf firing (%) compared with *L. perenne*. This difference can be explained by the fact that *F. arundinacea* exhibits a more advantageous adaptation to salt stress due to its deeper root system and effective osmotic balancing mechanisms (Gao and Li 2012; Perlikowski et al. 2019). Indeed, these findings are consistent with studies in the literature reporting that *Festuca* species exhibit higher salt tolerance compared to other cool climate species such as *Lolium* (Krishnan 2010; Kozłowska et al. 2021). Salt applications caused negative effects on all parameters except root dry weight in both species (Table 2). In particular, salinity caused declines in turf color and quality, increased leaf firing (%), and reduced chlorophyll content. Several studies have reported significant decreases in shoot and root dry weight, plant height and chlorophyll content in turfgrass species grown under NaCl-induced salt stress (Ali et al. 2020; Soleimannejad et al. 2019; Bano et al. 2022). The findings obtained within the scope of this study are also consistent with previous studies showing the sensitivity of cool climate turfgrass species to salinity (Harivandi et al. 1992; Marcum and Pessarakli 2006). For example, in a study on *L. perenne*, it was reported that 250 mM NaCl application reduced the vertical shoot growth rate and caused a decrease in shoot and root biomass (Meng et al. 2023). Similarly, previous research indicates that salt stress at 15–20 dS m^{-1} significantly affects physiological parameters such as chlorophyll content, relative water content, proline accumulation and electrolyte leakage in *Cynodon dactylon*, *F. arundinacea* and *L. perenne* species (Esmaeili et al. 2015). The observed responses at 6 dS m^{-1} salinity highlight the practical relevance of this stress level, as it reflects salinity conditions frequently reported in lawns irrigated with marginal or reclaimed water sources. Within this framework, the present study contributes to the literature by providing a direct, dose-dependent comparison of nano silicon and humic acid applications in two widely used cool-season turfgrass species under a defined and field-relevant salinity level.

The relatively lesser effect on root dry weight in the present study indicates that salt stress primarily suppresses shoot development, while root development shows a more complex and resistant stress response. Indeed, Maas (1990) stated that salt stress primarily limits shoot development, while roots can remain more tolerant or adapt in some cases. Similarly, Carrow and Duncan (1998) stated that salt stress can cause different levels of sensitivity on the shoot and root systems of plants, and that especially in turfgrass species, the upper part can be damaged more rapidly.

The results indicate that nano silicon and humic acid differed in their capacity to alleviate salt stress. Among the nano silicon treatments, NS200 consistently produced the most favorable responses across multiple parameters, including turf color, quality, chlorophyll content, clipping dry weight, and reduced leaf firing (%), with the exception of root and shoot dry weights. NS100 also improved several traits, but its effects were generally less pronounced than those observed for NS200. Notably, under a salinity level of 6 dS m^{-1}, turfgrass color and quality values obtained with NS200 were statistically comparable to the control,

highlighting the strong role of this biostimulant in enhancing salt stress tolerance. In contrast, humic acid at 300 cc da^{-1} showed moderate improvements in selected parameters such as leaf firing (%), chlorophyll content, and clipping dry weight, but overall exhibited lower effectiveness compared to nano silicon treatments. This relatively modest response is likely related to the dose-dependent nature of humic acid activity under salinity stress. Previous studies have shown that higher application rates or repeated applications of humic substances are often required to achieve significant physiological and growth responses in turfgrass under saline conditions (Daneshvar Hakimi Maibodi et al. 2015; Kazemi et al. 2019), and that suboptimal doses may result in limited stress mitigation (Canellas and Olivares 2014; Saeedi Pooya et al. 2018; Sharifiasl et al. 2019). Accordingly, the present findings suggest that the performance of humic acid should be interpreted within the context of dose dependency rather than as an indication of low biostimulant potential.

Nano silicon has been reported to contribute to the maintenance of cellular water balance, enhancement of antioxidant enzyme activities, regulation of ion homeostasis, and strengthening of defense mechanisms against salt toxicity (Luyckx et al. 2017; Siddiqui et al. 2014; Wang et al. 2015; Bhat et al. 2021). Recent studies further support these mechanisms, demonstrating that silicon nanoparticles enhance salt tolerance by stimulating antioxidant systems, reducing oxidative damage, and improving physiological stability under saline conditions (Ahmadi-Nouraldinvand et al. 2023; Narimani et al. 2025). Collectively, these findings indicate that nano silicon enhances salinity tolerance primarily through direct physiological regulation at the cellular level rather than indirect growth stimulation. For example, Chai et al. (2010) reported improved growth and quality in *Poa pratensis* under salinity stress following silicon application, while Taher et al. (2023) showed enhanced stress tolerance in turfgrass mainly through improved structural stability. In this context, the present study provides direct evidence that foliar-applied NS200 effectively mitigates salinity-induced damage in cool-season turfgrass species, as reflected by improvements in visual quality, chlorophyll content, and reduced leaf firing (%), suggesting enhanced physiological efficiency under moderate salinity stress.

The positive effects of humic acid on plant growth are explained by its direct hormone-like stimulatory activities as well as its indirect functions in regulating soil-water-nutrient relations (Canellas and Olivares 2014; Jindo et al. 2020; Shah et al. 2018). Many studies have shown that humic acid is effective in reducing the negative effects of salt stress on turfgrass species. Serious decreases in biomass are observed in plants exposed to salt stress; however, humic acid applications can compensate for this loss to a significant extent. For example, in their study on *L. perenne*, Meng et al. (2023) reported that humic acid application provided a significant increase in parameters such as vertical shoot growth rate, shoot and root dry weight, and biomass production approached control levels. Similarly, Kaya et al. (2018) showed that humic acid application in corn plants exposed to salt stress improved growth parameters by increasing both fresh and dry biomass.

It is reported that Si applications maintain the K^+/Na^+ balance by reducing Na^+ transport and accumulate in plant tissues, strengthen cell walls, and limit stress-related damages such as osmotic pressure, ionic toxicity, and water loss; thus, acting as a mechanical barrier (Mateos-Naranjo et al. 2013; Sharifiasl et al. 2019; Martínez-Lorente et al. 2024; Ahmadi-Nouraldinvand et al. 2023; Ma and Yamaji 2006). In contrast, it is stated that humic acid applications limit Na^+ uptake by increasing ion exchange capacity and promote the uptake of essential elements such as K^+, thus creating an environment that improves ionic selectivity at the soil-root interface (Merwad, 2017; Jarošová et al. 2016). Although humic acid was applied foliarly in this study, its effectiveness under the applied salinity level was lower than that of nano silicon. This suggests that under moderate salinity stress (6 dS m^{-1}), nano silicon may provide a more direct and rapid physiological response than humic acid. In contrast to nano silicon, humic acid appears to influence salinity responses mainly through indirect and dose-dependent pathways, which may explain its weaker and less consistent effects under the applied stress conditions. Previous studies have reported that humic substances often exhibit stronger growth-promoting and stress-mitigation effects when applied to the soil or root zone rather than via foliar spraying, primarily due to enhanced root–soil interactions and improved nutrient uptake (Calvo et al. 2014; Canellas et al. 2015; Jindo et al. 2020). Future studies could therefore further explore dose-response relationships and application methods for humic acid under varying salinity levels; however, the present study aimed to benchmark a commonly used foliar humic acid dose against different nano silicon application rates to evaluate their comparative performance.

In this study, it was determined that salt stress significantly reduced shoot dry weight in *L. perenne*; on the other hand, NS100 and H300 applications compensated this decrease. In *F. arundinacea*, no significant effect of both salt and biostimulant applications on shoot dry weight was observed. When evaluated in terms of root dry weight, it was found that the combination of 6 dS m^{-1} salt and NS200 provided a statistically significant increase in *F. arundinacea* compared to only NS200 application. However, there was generally no significant difference between the applications in terms of root dry weight both in saline and non-saline conditions. In *L. perenne*, salt stress had no significant effect on root dry weight, while NS200 and H300 applications applied in

non-saline conditions statistically decreased this parameter. In the literature, it is widely reported that both silicon and humic acid applications provide significant improvements in basic morphological parameters such as shoot and root length, fresh and dry weight. For example, Bae et al. (2012) reported that 0.1 mM silicon application in *Poa pratensis* species increased shoot length by 48%. Similarly, Kaya et al. (2018) and Ali et al. (2020) showed that humic acid applications provided shoot and root biomass increases exceeding 100% in grasses and different cultivars. Soleimannejad et al. (2019) reported that silicon application increased shoot dry weight by 29% in the halophytic *Puccinellia distans* species under 200 mM NaCl.

In the present study, shoot and root biomass responses to salinity and biostimulant applications differed between species and treatment combinations, indicating that biomass allocation under salt stress is influenced by both species-specific functional traits and the mode of action of applied biostimulants. In *L. perenne*, salinity stress significantly reduced shoot dry weight, while NS100 and H300 partially compensated for this reduction, suggesting improved tolerance of aboveground growth. In contrast, shoot dry weight in *F. arundinacea* remained relatively stable across treatments, consistent with its higher inherent salinity tolerance and deeper, more efficient root system (Marcum and Pessarakli 2006; Perlikowski et al. 2019).

Root biomass responses were more variable and appeared to depend on both stress presence and biostimulant application. Under saline conditions, the combination of 6 dS m^{-1} NaCl and NS200 significantly increased root dry weight in *F. arundinacea*, indicating that nano silicon may promote root system stability and adaptive growth under osmotic and ionic stress. Similar silicon-induced enhancements of root architecture and biomass under salinity have been reported in turfgrass and related species, including increased root elongation, density, and water uptake efficiency (Bae et al. 2012; Esmaeili and Salehi 2016; Zhang et al. 2020; Bhat et al. 2021). Overall, these findings support previous reports showing that salinity more strongly restricts shoot growth, whereas root responses are more complex and context-dependent (Maas 1990; Carrow and Duncan 1998).

Under non-saline conditions, certain biostimulant treatments, particularly nano silicon and humic acid, were associated with reduced root dry weight in *L. perenne*. This response is consistent with previous reports indicating that biostimulants often exert their strongest positive effects under stress, whereas under optimal conditions they may alter carbon allocation patterns or hormonal balance, leading to reduced investment in root growth (Canellas and Olivares 2014; Bulgari et al. 2019; Rouphael and Colla 2020). Similarly, the absence of a pronounced biostimulant-induced increase in root dry weight under saline conditions suggests that nano silicon primarily enhanced salt tolerance through improved physiological efficiency and ion homeostasis rather than by stimulating root proliferation. Such trade-offs between shoot and root development, together with dose-dependent and formulation-specific effects of silicon and humic substances, have been widely reported and highlight the importance of stress intensity, specie Canellass-specific traits, and appropriate dose selection when interpreting biomass responses to biostimulant applications (Van Oosten et al. 2017; Canellas et al., 2015).

Although the reduction in root dry weight under non-saline conditions may appear inconsistent with the commonly reported growth-promoting effects of biostimulants, this response supports the view that their benefits are primarily expressed under stress conditions. Under optimal environments, external biostimulant applications may alter physiological balance and carbon allocation patterns, potentially reducing root investment (Canellas and Olivares 2014; Canellas et al., 2015). In turfgrass species, resource allocation is often directed toward shoot growth under non-stress conditions, resulting in relatively lower root biomass (Carrow and Duncan 1998). These responses highlight the importance of dose, formulation, and environmental context when interpreting root growth responses to biostimulant applications. In terms of chlorophyll content, both silicon and humic acid applications exhibited positive effects on turfgrass species. Silicon, in particular, has been shown to enhance physiological resistance by protecting photosynthetic pigments under salinity stress. Previous studies reported substantial increases in chlorophyll content and visual quality following silicon application in *Poa pratensis*, *Festuca*, and *Lolium* species, even under high NaCl concentrations (Bae et al. 2012; Esmaeili et al. 2015). These effects have been attributed to mechanisms such as reduced ethylene production, stabilization of chloroplast structure, and improved light interception through enhanced leaf posture (Esmaeili and Salehi 2016; Ahmadi-Nouraldinvand et al. 2023; Narimani et al. 2025).

On the other hand, it is suggested that humic acid applications increase chlorophyll a, b, and total pigment contents, and this effect is mostly realized through enzymatic activation and improvement of mineral uptake (Merwad et al., 2017). Humic acid has been reported to enhance chlorophyll accumulation by stimulating enzymatic and metabolic processes associated with photosynthetic pigment synthesis and by improving photosynthetic efficiency, particularly under abiotic stress conditions (Van Oosten et al. 2017; Bulgari et al. 2019; Rouphael and Colla 2020). El-Sayed et al. (2017) and Sharifiasl et al. (2019) also stated that humic acid provides significant contributions to photosynthetic efficiency and visual quality by increasing total chlorophyll and carotenoid contents.

Salt application caused a marked decline in visual quality and color values in both turfgrass species; however, the effectiveness of biostimulant treatments varied depending on species and application dose. In *F. arundinacea*, NS100 application partially alleviated these negative effects, whereas NS200 and H300 did not result in sufficient improvement. In contrast, in *L. perenne*, NS200 application effectively mitigated visual quality losses under salinity stress, while NS100 and H300 showed no significant effects. These findings indicate that turfgrass species respond differently to the same biostimulants depending on dose level, which is consistent with species-specific and dose-dependent responses reported in the literature (Ronga et al. 2019; Martínez-Lorente et al. 2024).

In terms of visual quality, the literature consistently emphasizes that humic acid applications exhibit a high capacity to improve leaf color, tissue homogeneity, and aesthetic appearance after cutting. Saeedi Pooya et al. (2018) reported that humic acid application darkened turfgrass color, reduced leaf coarseness, and enhanced overall aesthetic appearance after mowing, while Kazemi et al. (2019) similarly demonstrated improved visual quality and color uniformity. Daneshvar Hakimi Maibodi et al. (2015) further showed that a 1000 mg L^{-1} humic acid application increased visual quality by 13% in *L. perenne*. Collectively, these studies confirm that humic acid is an effective biostimulant for enhancing aesthetic traits of turfgrass.

In contrast to humic acid, silicon-based applications primarily enhance mechanical durability and stress tolerance by stiffening plant posture and reinforcing cell wall structure, rather than directly influencing pigment synthesis or aesthetic traits. Taher et al. (2023) demonstrated that silicon-based treatments improve structural strength and stress resistance mainly through enhanced mechanical stability. This distinction suggests that humic acid functions predominantly through hormonal regulation and pigment-related pathways that improve aesthetic quality, whereas nano silicon contributes more strongly to physiological stability and stress tolerance under salinity. Taken together, these findings suggest that humic acid is more closely associated with improvements in visual quality, while nano silicon provides a more consistent contribution to stress resilience in turfgrass systems.

Conclusion

This study demonstrates that nano silicon application, particularly at a rate of 200 cc da^{-1}, effectively mitigates salinity-induced stress in cool-season turfgrass species under controlled greenhouse conditions. The NS200 treatment resulted in marked improvements in physiological performance and visual quality parameters, including turf quality, chlorophyll content, and reduced leaf firing (%), whereas humic acid applied at the tested dose exhibited comparatively limited effects under the same salinity level.

Overall, these findings indicate that nano silicon is a promising biostimulant for enhancing salinity tolerance in cool-season turfgrass systems. However, the results should be interpreted considering the study's limitations, including the use of controlled greenhouse conditions, a single salinity level, and a single humic acid application rate. Future research should therefore focus on broader dose–response relationships, combined biostimulant applications, and long-term field experiments to validate the observed effects under practical turfgrass management conditions.

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Declarations

Conflict of interest The authors declare no competing interests.

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