

Article

Effect of Zeolite Amendment on Growth and Functional Performance of Turfgrass Species

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Abstract

Progressive urbanization and increasing pressure on urban green areas necessitate the search for innovative, ecological, and efficient solutions for lawn management. The shallow root system of grasses, combined with a long vegetation period, makes these plants particularly sensitive to water and nutrient deficiencies. One research direction involves the use of zeolites, natural aluminosilicate minerals that, due to their porous structure and high sorption capacity, improve water retention and nutrient availability in soil. The aim of this study was to assess the effect of different zeolite doses on the initial growth and development of two turfgrass species (*Lolium perenne*, *Festuca rubra*), as well as on selected lawn performance traits, and to determine the persistence of these effects over time. This research was conducted in 2020–2023 under pot and micro-plot experiment conditions, using mixtures containing the above species. Four levels of zeolite addition to the substrate were applied: 0% (control), 1%, 5%, and 10%. The results clearly confirmed the beneficial effects of zeolite. Its addition improved the germination, growth, and biomass yield of aboveground parts and roots, as well as enhancing turf aesthetics, ground cover, and winter hardiness, while reducing the proportion of dicotyledonous species. The best effects were obtained with the 5% dose, which should be considered optimal—it significantly improved lawn utility parameters with lower material input compared to the 10% dose. Species response varied: *L. perenne* responded more strongly to improved water–air conditions, whereas *F. rubra* utilized higher zeolite doses more effectively in root system development. The highest overall effectiveness was recorded with the 10% dose. Zeolite effectiveness was greatest in the first year after application, showing a declining trend in subsequent years, although a positive effect was still observed in the third year of use. The findings support the recommendation of zeolite as an ecological soil additive that enhances lawn quality and durability, particularly in low-fertility soils and under water deficit conditions. Its application may represent an important component of modern green space management technologies in line with the principles of sustainable development.

Keywords: grass growth and development; lawn; lawn grass species; zeolite



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1. Introduction

The progressive urbanization and intensive transformation of the natural environment necessitate the continuous search for innovative solutions, including those related to urban green space management. Green space management is a crucial element in shaping these areas by modifying their aesthetics and spatial functionality—both public and private [1].

Lawns are among the fundamental components of green areas [2]. Grass vegetation, which constitutes their main element, on the one hand creates recreational spaces and enhances the aesthetic qualities of the surroundings, while on the other plays a key role in shaping the microclimate, protecting soil against erosion, and improving air quality, thereby contributing to a better quality of life for residents [3]. However, the shallow root system of grasses and their long vegetation period make them particularly sensitive to water and nutrient deficiencies [4,5]. This issue is especially evident in anthropogenic areas such as newly developed housing estates and home gardens, where soils often exhibit low fertility and disturbed moisture conditions [6]. Maintaining high-quality turf under conditions of strong anthropogenic pressure requires advanced maintenance technologies, often involving considerable water consumption, as well as the use of pesticides and fertilizers. The need to reduce costs and nutrient losses to the environment creates a demand for innovative materials that support grass growth, increase fertilization efficiency, and at the same time minimize negative environmental impacts.

One such material is zeolite—a natural aluminosilicate mineral which, due to its porous structure, cation-exchange capacity, and high sorption potential, can positively influence soil water retention and reduce nutrient leaching [7,8]. Its use in agronomy contributes to improved soil fertility, enhanced plant tolerance to abiotic stresses (e.g., water deficit, salinity), and reduced uptake of heavy metals [9–11].

With growing ecological awareness and the push toward sustainable development, the use of materials such as zeolites appears to be a promising direction with considerable application potential [12]. Although studies on the response of turfgrass to zeolite application exist, most previous research has focused on agricultural and vegetable crops; therefore, the present study provides a valuable contribution to advancing knowledge in this field. The obtained results may therefore be applicable not only in the practice of urban green space maintenance but also in agricultural holdings, and they may contribute to the advancement of research on innovative green space management technologies. At the same time, they address the need to identify effective methods for improving lawn quality and durability while reducing maintenance costs and environmental impacts.

The objective of the present study was to evaluate the effect of different doses of zeolite mixed with soil substrate on the growth and development of two turfgrass species (*Lolium perenne* and *Festuca rubra*) and on selected lawn performance traits. Particular attention was given to interspecific differences in response to the presence of zeolite in the soil, as well as to the persistence of its effects over time. The results were intended to provide a basis for assessing the suitability of zeolite as an additive that improves soil water–air relations and supports effective green space management, particularly under conditions of low fertility and water deficit.

This study aimed to determine how the addition of zeolite to the soil substrate affects the growth and development of turfgrass and the utility traits of lawn turf, which zeolite dose (1%, 5%, or 10%) is most effective in improving performance parameters, whether plant response to zeolite application differs between the two grass species, and whether the effect of zeolite persists over time or weakens in subsequent growing seasons.

It was hypothesized that the application of zeolite in the soil substrate improves germination, growth, and development of turfgrass, with its effectiveness depending on the applied dose and species response. It was further assumed that the highest effect

would be achieved at higher zeolite doses (5% and 10%) and in species with greater habitat requirements. In addition, it was expected that zeolite addition would improve turf aesthetics, enhance resistance to environmental stress, and reduce the share of undesirable plants. Finally, it was hypothesized that the effect of zeolite would persist over time, although its effectiveness might gradually decrease in subsequent years of use.

2. Materials and Methods

The experimental work was designed to verify the research hypothesis assuming a positive effect of different zeolite doses on the initial growth and development of turfgrass species with varying water requirements. This study was conducted in 2020–2023 using pot and micro-plot experiments at the Didactic and Research Station in Sosnowica (Parczew County), belonging to the Department of Grassland and Landscape Shaping of the University of Life Sciences in Lublin.

The mineral soil used in both plot and pot experiments belonged to the agronomic category of light soils and was characterized by a slightly acidic reaction (pH 5.89), medium phosphorus availability (14.3 mg P₂O₅ per 100 g soil), low potassium content (8 mg K₂O per 100 g soil), and medium magnesium content (4.8 mg per 100 g soil). The zeolite used in this study (natural clinoptilolite) originated from a commercial deposit in Ukraine (Zakarpattia region Sokyrnytske, Sokyrnytsya, Ukraine) and was imported by an entrepreneur collaborating with the University of Life Sciences in Lublin. It was characterized by a slightly acidic reaction (pH 5.2). It was distinguished by high sorption capacity, indicating considerable cation-exchange ability and potential for binding both nutrients and contaminants. In terms of granulometry, the zeolite consisted mainly of the 0.5–1 mm fraction, which accounted for 89.66% of the sample mass. The concentrations of heavy metals did not exceed permissible limits established for fertilizers and plant growth-supporting agents [11].

2.1. Pot Experiment—Experimental Design

The pot experiment was established in 2020 in a completely randomized design with four replications. Pots were filled with 5 kg of soil mixed with zeolite at different doses: 1, 5, and 10%, corresponding to 10, 50, and 100 g per 1 kg of substrate, respectively. The control object consisted of soil without zeolite addition (Table 1). The zeolite application rates (1%, 5%, and 10% *w/w*) were selected based on previous studies that applied similar levels to evaluate the effects of zeolite on soil physical and water properties [13–15]. The 1% level corresponds to a typical organic fertilizer application rate (approximately 30 t·ha^{−1}), whereas the 5–10% range is commonly considered optimal for improving soil water retention and structure [13,16].

Table 1. Scheme of the pot experiment conducted at the Didactic and Research Station in Sosnowica.

Replication		Mixture (M1)			Mixture (M2)			
1	Z 0	Z 1%	Z 5%	Z 10%	Z 0	Z 1%	Z 5%	Z 10%
2	Z 0	Z 1%	Z 5%	Z 10%	Z 0	Z 1%	Z 5%	Z 10%
3	Z 0	Z 1%	Z 5%	Z 10%	Z 0	Z 1%	Z 5%	Z 10%
4	Z 0	Z 1%	Z 5%	Z 10%	Z 0	Z 1%	Z 5%	Z 10%

Each year in spring (immediately after the beginning of the growing season), seeds of two turfgrass mixtures were sown at a rate of 30 seeds per pot. Mixture 1 was composed of four *L. perenne* cultivars (Bokser, Nira, Stadion, Elegana) in equal weight proportions (25% each), while Mixture 2 consisted of four *F. rubra* cultivars (Magitte, Rossinante, Nista, Nimba) in equal proportions (25% each). These species differ in water requirements—*L. perenne* prefers

more humid habitats, whereas *F. rubra* tolerates conditions ranging from moderately moist to dry (Figure 1).

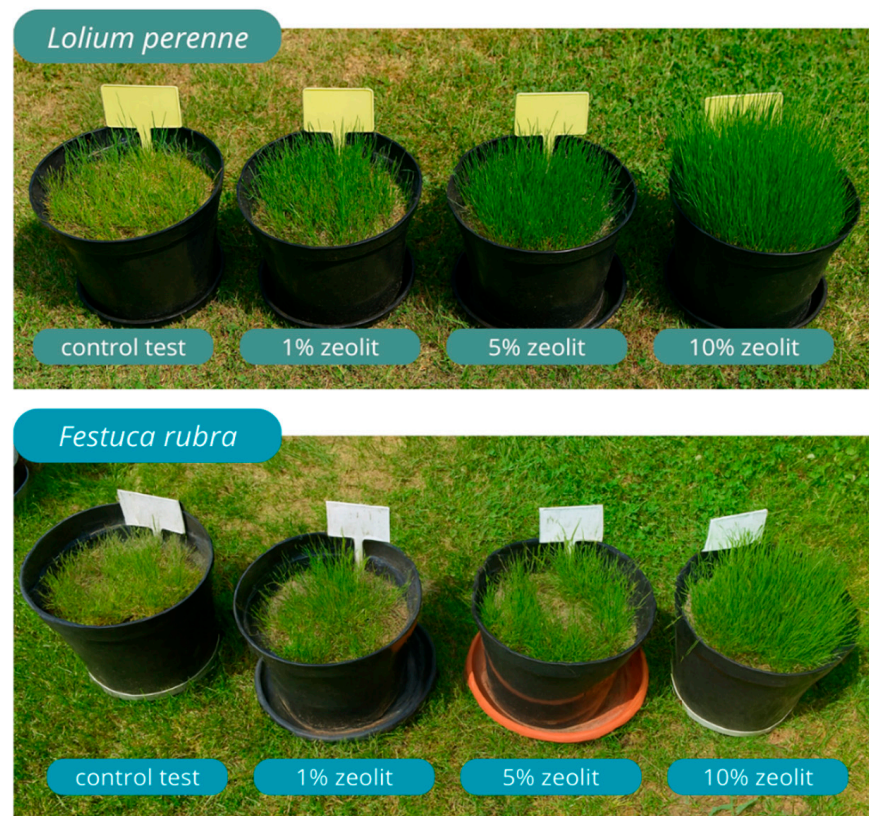


Figure 1. View of one set of the pot experiment evaluating the effect of different zeolite doses (0%, 1%, 5%, and 10%) on the growth and development of turfgrass cultivars *Lolium perenne* (M1) and *Festuca rubra* (M2). The experiment included four replications for each treatment.

Fertilization with N, P, and K was applied at constant levels: nitrogen— $0.25 \text{ mg} \cdot \text{kg}^{-1}$ of soil in the form of ammonium nitrate, phosphorus— $0.3 \text{ g} \cdot \text{kg}^{-1}$ (triple superphosphate), and potassium— $0.9 \text{ g} \cdot \text{kg}^{-1}$ (as KCl). Fertilization was applied in split doses. Before sowing, the full dose of phosphorus and potassium, along with approximately 40% of the total nitrogen rate, was incorporated into the soil. The remaining nitrogen was applied as top dressing in two equal portions, immediately after the first and second cuts, respectively. Before sowing, substrate moisture in each pot was adjusted to the same level corresponding to 60% of field capacity. The field capacity of the soil used to fill the pots was determined under field conditions. The soil was placed in four identical containers and saturated with water, then left for 48 h to allow gravitational water to drain freely. After this period, soil samples were weighed in their wet state, then oven-dried at 105°C to constant weight. Field capacity was calculated as the difference between the wet and dry sample weights relative to the dry weight, and the average value was expressed as a percentage. After establishing the initial moisture level, the pots were placed outdoors on a special platform under the natural climatic conditions of the experimental station, without additional irrigation, and were exposed solely to prevailing weather conditions. This approach allowed the natural course of changes in substrate moisture to be reflected depending on the applied zeolite dose.

In the pot experiment, seedling emergence (%) was assessed after 14 days from sowing *L. perenne* seeds and after 21 days from sowing *F. rubra* seeds (according to ISTA 2012 [17]). In addition, the number of normal seedlings, abnormal seedlings, and dead seeds (%) was recorded, after which abnormal seedlings and dead seeds were removed. An equal number

of plants (20 per pot) was maintained in each pot, and their height was measured every 10 days.

During each growing season, the grasses were cut three times at a height of 3–4 cm, and the yield of aboveground green biomass (g/pot) recorded. At the end of each growing season, plant roots were collected from the pots, washed under running water on fine-mesh sieves, and after draining, root yields were determined by weight (g/pot).

2.2. Micro-Plot Experiment—Experimental Design

The field experiment was conducted in 2021–2023 in a completely randomized design with three replications under natural rainfall conditions without supplemental irrigation. Each micro-plot had an area of 1 m² and was separated from the next one by a 50 cm strip of bare soil. Zeolite was added and mixed with soil in the 0–20 cm layer at rates of 1, 5, and 10%, corresponding to 3, 15, and 30 kg, respectively (assuming a soil mass of 300 kg per 1 m²). The control plots consisted of micro-plots without zeolite addition (the experimental design was the same as in the pot experiment).

In all plots, turfgrass sod was applied (sourced from a company specializing in turf production) with a species composition specially prepared for this study, as shown in Table 2 and Figure 2.

Table 2. Species composition of the Stadion 1 turfgrass sod used in the micro-plot experiment.

Grass Species and Turf Variety	Proportion in Turf (%)
<i>L. perenne</i> cv. Bokser	20
<i>L. perenne</i> cv. Nira	20
<i>L. perenne</i> cv. Stadion	15
<i>L. perenne</i> cv. Elegana	5
<i>F. rubra</i> cv. Magitte	10
<i>F. rubra</i> cv. Rossinante	10
<i>F. rubra</i> cv. Nista	10
<i>F. rubra</i> cv. Nimba	10



Figure 2. View of the microplot experiment evaluating the effect of zeolite addition (0%, 1%, 5%, and 10%) on turfgrass quality and functional properties. (a) Establishment of the experiment, (b) first year of the experiment, (c) second year of the experiment. The trial was conducted at the Didactic and Experimental Station in Sosnowica, belonging to the Department of Grassland and Landscape Shaping.

Each year during the growing season, all plots received uniform mineral fertilization (N—150, P—88, K—144 kg·ha^{−1}). Phosphorus and potassium fertilizers were applied twice: in the third decade of April and in August, whereas nitrogen fertilizers were divided into three doses and applied after each mowing.

Each year in spring (one week after the onset of vegetation, i.e., the appearance of new green shoots and the resumption of grass growth, typically in late March or early April) and in autumn (October), the effect of different zeolite doses on turf density and the share of dicotyledonous species in the sward was evaluated. These parameters were evaluated

using Weber’s quadrat method [18]. At the same time, the overall visual quality of turf was evaluated (a synthetic indicator of sod aesthetics and quality, taking into account color, density, uniformity, and general visual impression), while winter survival was assessed only in spring. Evaluations were performed using the nine-point scale applied by COBORU (Research Centre for Cultivar Testing, Słupia Wielka, Poland), where a score of 9 indicates very good condition and a score of 1 corresponds to turf of very poor quality (Table 3). From the perspective of assessing the biological, compositional, and aesthetic value of lawn turf, a difference of 1 point is considered significant [19]. In the first year of the experiment, assessments were carried out in summer (July) and autumn (as above).

Table 3. Evaluation scale for the assessed utility traits of lawn turfgrass.

Scale	Trait		
	General Aspect	Turf Cover	Winter Survival
1	Poor	poor (no leaves)	Poor
3	Weak	weak	Weak
5	Fair	fair	Average
7	Good	good	Good
9	very good	very good (perfectly uniform turf)	very good

Source: [19].

The turf was mown four times per year to a height of 4 cm, with mowing dates determined by weather conditions and the rate of regrowth. Yields of aboveground green biomass (Q , $g \cdot m^{-2}$) were recorded.

Statistical analysis of the results from both experiments was performed using SAS software (version 9.1), applying analysis of variance (ANOVA) and Tukey’s test at a significance level of $\alpha \leq 0.05$. In the pot experiment, the statistical model included the following factors: turfgrass mixture (M1 and M2), zeolite dose (0%, 1%, 5%, 10%), and—in the case of yield analysis—regrowth (I, II, III). Interactions between these factors were also evaluated: mixture $\times$ dose, mixture $\times$ regrowth, dose $\times$ regrowth, and mixture $\times$ dose $\times$ regrowth. In the microplot experiment, the effects of zeolite dose and year of study (2021–2023) were analyzed, and selected parameters were also subjected to interaction analysis between year and zeolite dose (year $\times$ dose). Means followed by the same letters do not differ significantly according to Tukey’s HSD test.

2.3. Weather Conditions During the Study Period

Meteorological data from 2020–2023 and from the long-term period 1991–2020 indicate clear changes in weather conditions that influenced plant growth and development in the study region. In 2020–2023, the mean annual air temperature ranged from 7.8 °C in 2021 to 9.8 °C in 2023, exceeding the long-term average of 8.0 °C (Table 4). Notably, 2023 was the warmest year of the study period, while 2021 was the coldest.

Precipitation during the study years showed high variability. Annual totals ranged from 635 mm in 2022 to 690 mm in 2023, while in the growing seasons these values ranged from 445 mm in 2023 to 544 mm in 2020. Compared with the long-term totals, they were higher, as the multi-year annual precipitation amounted to 627 mm and 423 mm in the growing season. The highest growing season totals were recorded in 2020, and June in particular, was characterized by rainfall three times higher than the long-term average for that month.

Table 4. Air temperature (°C) and precipitation (mm) in 2020–2023 and in the long-term period 1991–2020.

Year	Month												Period	Annual
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	IV–X	
Mean air temperature [°C]														
2020	2	2	4	8	11	18	18	20	15	10	5	2	14.3	9.6
2021	−2	−3	2	7	12	19	21	17	12	8	3	−2	13.7	7.8
2022	1	2	3	7	13	19	19	20	11	10	3	−1	14.1	8.9
2023	2	1	4	9	14	17	19	21	17	10	3	1	15.3	9.8
1991–2020	−2	−2	2	9	12	17	19	18	13	9	3	−1	13.9	8
Mean precipitation [mm]														
2020	25	45	35	9	85	220	35	75	65	55	15	25	544	689
2021	55	15	15	55	45	76	90	200	55	10	35	30	531	681
2022	20	35	20	40	55	45	130	70	105	30	20	65	475	635
2023	70	30	45	40	90	65	110	70	15	55	60	40	445	690
1991–2020	30	34	45	40	65	70	80	70	55	43	45	50	423	627

Source: own elaboration based on klimat.imgw.pl data.

3. Results

3.1. Pot Experiment—Results and Analysis

3.1.1. Seedling Emergence

Analysis of the effect of zeolite on the initial development of grasses in mixture 1 revealed a tendency for seedling emergence efficiency to increase with higher zeolite doses in the substrate (Figure 3). However, significantly better emergence (compared to the control) was recorded only in objects with the highest (10%) zeolite dose. A similar relationship was observed for mixture 2, dominated by *F. rubra*. In this case, as well, emergence improved with increasing zeolite content in the substrate. Statistically significant improvements compared to the control (without zeolite) were found at 5% and 10% doses. However, the differences between these two doses were not statistically significant. Regardless of mixture, the 5% zeolite dose proved most effective, while increasing the dose to 10% did not cause further significant improvement.

3.1.2. Seedling Height

This study revealed a differentiated response of turfgrass species, measured by seedling height, to the addition of zeolite at varying doses. For mixture 1 (*L. perenne*), seedling height increased with rising zeolite content, and the difference between the control and the 10% dose was statistically significant ($p \leq 0.05$) (Figure 4).

Intermediate doses (1% and 5%) produced values that did not differ significantly from either the control or the 10% treatment. In mixture 2 (*F. rubra*), seedling height remained relatively stable across treatments, with no statistically significant differences among doses. Overall, a noticeable effect of zeolite on seedling height was confirmed only at the 10% dose in *L. perenne*, while *F. rubra* showed a more uniform growth pattern regardless of zeolite level.

3.1.3. Yield of Aboveground and Root Green Biomass of Grasses

Assessment of aboveground green biomass yields in relation to zeolite doses (0%, 1%, 5%, and 10%) and mixture type, conducted at three harvest times, showed that the application of zeolite affected turfgrass productivity, although the direction and magnitude of the response varied between species (Table 5).

During the first harvest, both mixtures produced higher yields compared with the control, particularly at the 1% and 5% zeolite doses. The response was more pronounced in

L. perenne (mixture 1), where yield increased from approximately 38 g·pot⁻¹ in the control to over 70 g·pot⁻¹ at 5%. In *F. rubra* (mixture 2), an increase was also observed—from about 24 g·pot⁻¹ to 44 g·pot⁻¹—although the differences between higher doses were smaller.

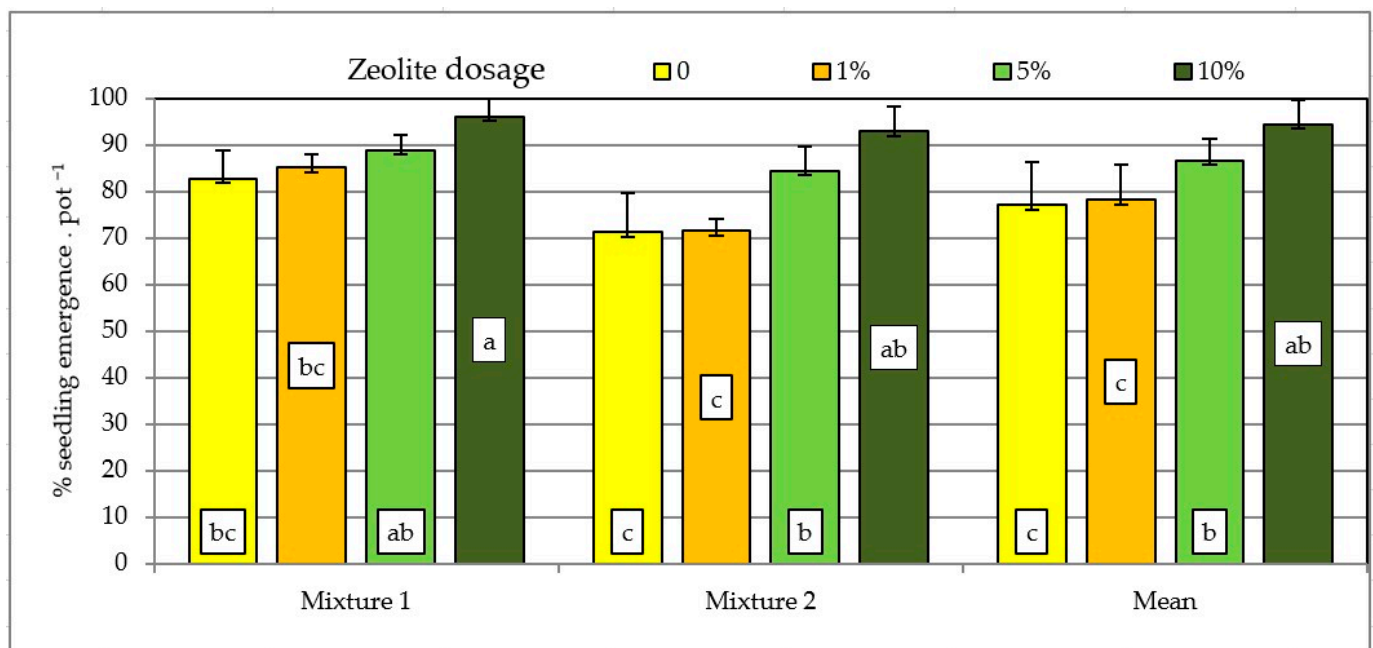


Figure 3. Effect of different zeolite doses on turfgrass seedling emergence (mean of 2020–2023). Values represent means of replications and years. Error bars show standard deviation. Different letters indicate statistically significant differences between groups (Tukey's HSD test, $p \leq 0.05$).

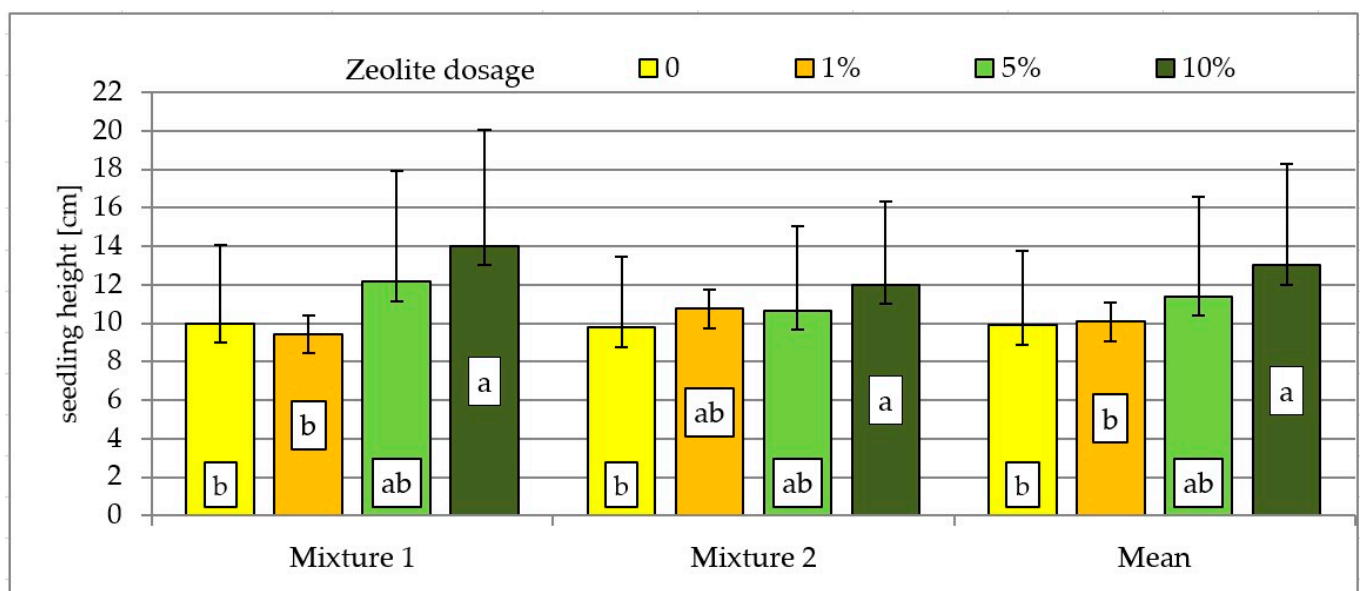


Figure 4. Effect of different zeolite doses on seedling height of turfgrass cultivars (mean of 2020–2023). Values represent means of replications and years. Error bars show standard deviation. Different letters indicate statistically significant differences between groups (Tukey's HSD test, $p \leq 0.05$).

In the second harvest, the relationships were less consistent. In mixture 1, the highest yield (approximately 64 g·pot⁻¹) was recorded at 5% zeolite, while the lowest values (around 40 g·pot⁻¹) occurred at 1% and 10%, suggesting that too low or too high a dose may reduce yield efficiency. *F. rubra* (mixture 2) maintained relatively uniform yields (49–56 g·pot⁻¹) across all zeolite treatments, clearly higher than in the control.

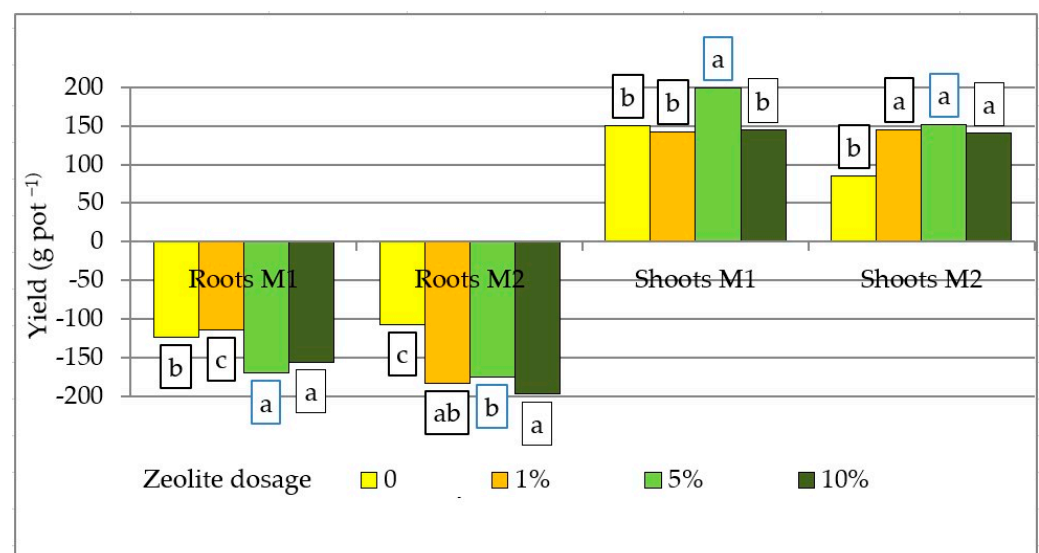
Table 5. Effect of zeolite dose on the mean green biomass yield of turfgrass in successive harvests (mean of 2020–2023).

Harvest	Zeolite Dose (%)	Yield Mixture 1 (g·pot ^{−1}) ± SD	Yield Mixture 2 (g·pot ^{−1}) ± SD
I	0	^b 38.08 ± 3.69	^b 24.29 ± 7.81
	1	^a 64.15 ± 15.75	^a 44.1 ± 7.55
	5	^a 71.29 ± 13.99	^a 39.3 ± 15.69
	10	^a 57.96 ± 2.93	^a 41.4 ± 3.45
II	0	^a 56.74 ± 7.34	^b 27.11 ± 11.25
	1	^b 39.57 ± 6.7	^a 50.78 ± 6.25
	5	^a 64.45 ± 5.4	^a 56.29 ± 6.71
	10	^b 43.46 ± 12.63	^a 49.48 ± 1.23
III	0	^a 55.1 ± 3.27	^b 33.48 ± 5.94
	1	^b 38.96 ± 11.0	^a 50.7 ± 10.42
	5	^a 63.75 ± 2.91	^a 56.21 ± 10.87
	10	^b 43.29 ± 16.66	^a 49.4 ± 5.57

Explanation: Different letters within the same harvest indicate significant differences (Tukey's HSD test, $p \leq 0.05$); identical letters indicate no significant differences.

In the third harvest, the differences between treatments persisted. In mixture 1, the highest yield (about 64 g·pot^{−1}) was again obtained at 5% zeolite, while lower values occurred at 1% and 10%. In *F. rubra* (mixture 2), the maximum yield (approximately 56 g·pot^{−1}) was recorded at the 5% dose, confirming a moderate but positive response to zeolite addition.

Mean annual aboveground biomass yields (Figure 5) indicate that *L. perenne* generally produced greater biomass than *F. rubra*, although the response pattern differed. In *L. perenne*, the highest values were consistently obtained at the 5% zeolite level, whereas in *F. rubra*, yields were more stable and less dependent on dose.

**Figure 5.** Effect of zeolite dose on the yield of aboveground (shoots) and root biomass of turfgrass mixtures (mean of 2020–2023). Data are expressed as grams of fresh weight per pot. Different letters indicate statistically significant differences between groups (Tukey's HSD test, $p \leq 0.05$).

Analysis of root biomass yields (Figure 5) revealed clear interspecific differences. In *L. perenne*, the highest root yield (approximately 170 g·pot^{−1}) was recorded at the 5% zeolite dose, while lower and higher doses produced smaller values. In contrast, *F. rubra* showed a gradual increase in root biomass with increasing zeolite content—from about 110 g·pot^{−1} in the control to approximately 195 g·pot^{−1} at 10%.

The obtained results confirm the beneficial, though species-specific, effect of zeolite on the growth of turfgrass species. The optimal zeolite rate for *L. perenne* is around 5%, while *F. rubra* responds positively even at the highest applied level (10%).

3.2. Micro-Plot Experiment—Results and Analysis

3.2.1. Turf Cover

The results obtained over successive years and at different zeolite doses indicate variation in its effectiveness in maintaining turf durability and quality. Zeolite dose had a statistically significant effect on the degree of turf cover, with clear benefits observed mainly at the 5% and 10% additions. The effect of zeolite was generally consistent over the three years, although statistical analysis did not confirm a significant dose $\times$ year interaction. Nevertheless, the overall turf cover declined in the third year of use (Figure 6).

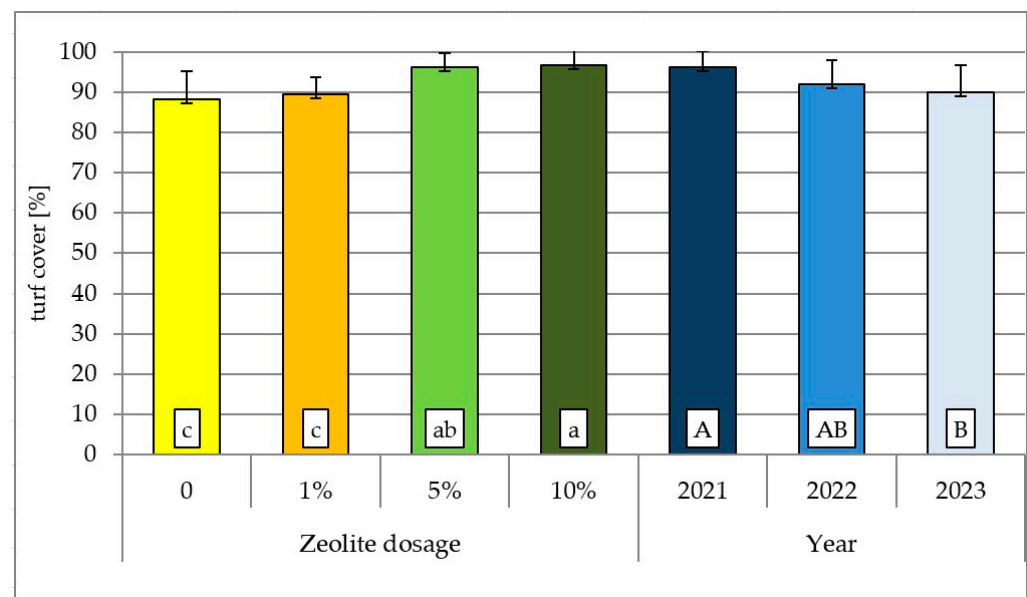


Figure 6. Turf cover in relation to zeolite dose and years of use (mean of 2021–2023). Values represent means of replications and years. Error bars show standard deviation. Bar colors indicate zeolite doses (0%, 1%, 5%, 10%) and years of use (2021, 2022, 2023). Different lowercase letters indicate significant differences between zeolite doses, and uppercase letters indicate differences between years (Tukey's HSD test, $p \leq 0.05$).

In the first year of the experiment (2021), turf cover was high across all treatments, and statistically significant differences were observed only between the 1% and 10% zeolite doses. In 2022, a slight decrease in turf cover was recorded; however, the general trend remained consistent, with the lowest values observed at the 1% zeolite dose. In the third year (2023), statistically significant differences were found between the control and the higher zeolite doses. The mean turf cover in the control plots was slightly above 80%, whereas significantly higher values were obtained at the 5% and 10% doses—93% and 95%, respectively. These results confirm the beneficial effect of zeolite compared with the control, particularly at higher application levels (Tables 1 and S1).

3.2.2. Share of Dicotyledonous Species

Maintaining high lawn quality requires controlling the species composition of turf, including the proportion of dicotyledonous species, as these often represent undesirable competitors to turfgrasses. Analysis of variance showed that both zeolite dose and year of use had a significant effect on the share of dicotyledonous species ($p < 0.001$). A significant interaction between these factors was also observed ($p \approx 0.027$). Tukey's test indicated

that only the 5% and 10% doses significantly reduced the share of dicotyledonous species compared with the control, while the 1% dose did not differ significantly from the control. Differences among the 1%, 5%, and 10% doses were not statistically significant (Figure 7).

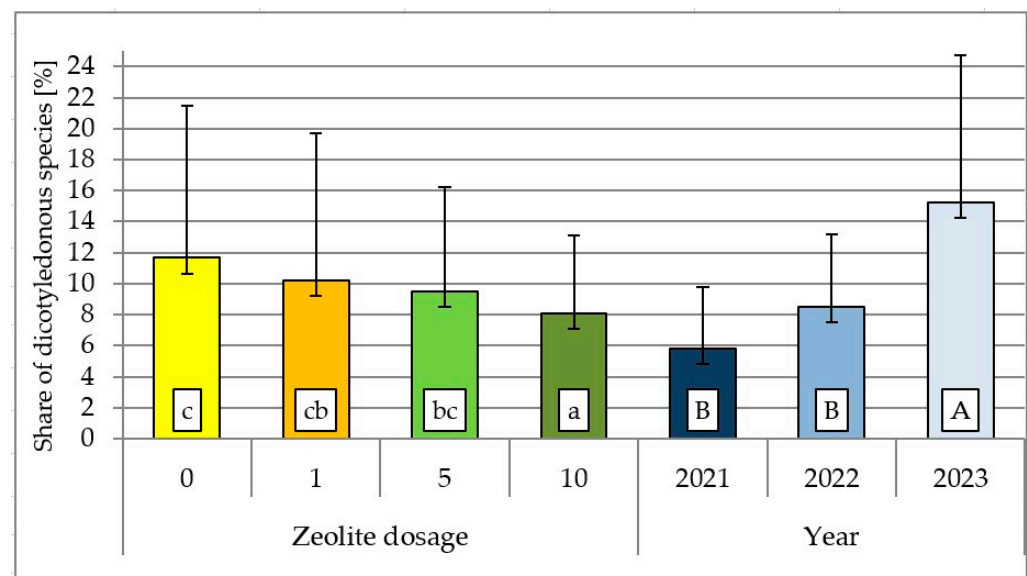


Figure 7. Effect of different zeolite doses on the share of dicotyledonous species in lawn turf (mean of 2021–2023). Values represent means of replications and years. Error bars show standard deviation. Bar colors indicate zeolite doses (0%, 1%, 5%, 10%) and years of use (2021, 2022, 2023). Different lowercase letters indicate significant differences between zeolite doses, and uppercase letters indicate differences between years (Tukey’s HSD test, $p \leq 0.05$).

Upon analyzing temporal trends, the highest share of dicotyledonous species was recorded in 2023. In 2021, the highest dose (10%) significantly reduced the share of dicotyledonous species. In 2022 and 2023, differences among the 0%, 1%, and 5% doses were not statistically significant, which may indicate decreasing effectiveness of lower doses in subsequent seasons (Tables 1 and S1).

3.2.3. Overall Visual Quality of Turf

Evaluation of overall turf appearance made it possible to determine the effect of zeolite on its aesthetics, density, and health—key traits that define its utility value. Two-way analysis of variance confirmed a significant effect of both zeolite dose ($p < 0.001$) and year ($p < 0.001$), with a significant interaction between these factors ($p < 0.001$). The 5% and 10% additions improved turf appearance relative to the control, whereas the 1% dose did not differ significantly from either 0% or 5% (Figure 8).

With each successive year, the overall turf rating declined. The effect of zeolite was strongest in the first year after application and weakened over time. In 2021, the highest score was obtained at the 10% dose (above 8.0 points), while the remaining treatments ranged from 7.6 to 8.0 points. In 2022—under favorable weather conditions—only the 10% dose produced a significant aesthetic effect. In 2023, under water and heat stress, all ratings declined, but once again the 10% dose performed best, highlighting its buffering effect on turf quality (Tables 1 and S1).

3.2.4. Green Biomass Yield

Analysis of variance showed that both zeolite dose ($p < 0.05$) and year of use ($p < 0.001$) significantly affected aboveground biomass yield. However, no interaction between these factors was observed ($p = 0.8737$), indicating that the zeolite effect was stable over time.

Mean yields increased slightly with higher zeolite doses, with the 5% and 10% treatments producing significantly greater values than the control (Figure 9). Nevertheless, the year effect was much stronger: yields were highest in 2021, decreased in 2022, and were lowest in 2023. This pattern reflects a gradual decline in turf productivity over time, regardless of zeolite treatment.

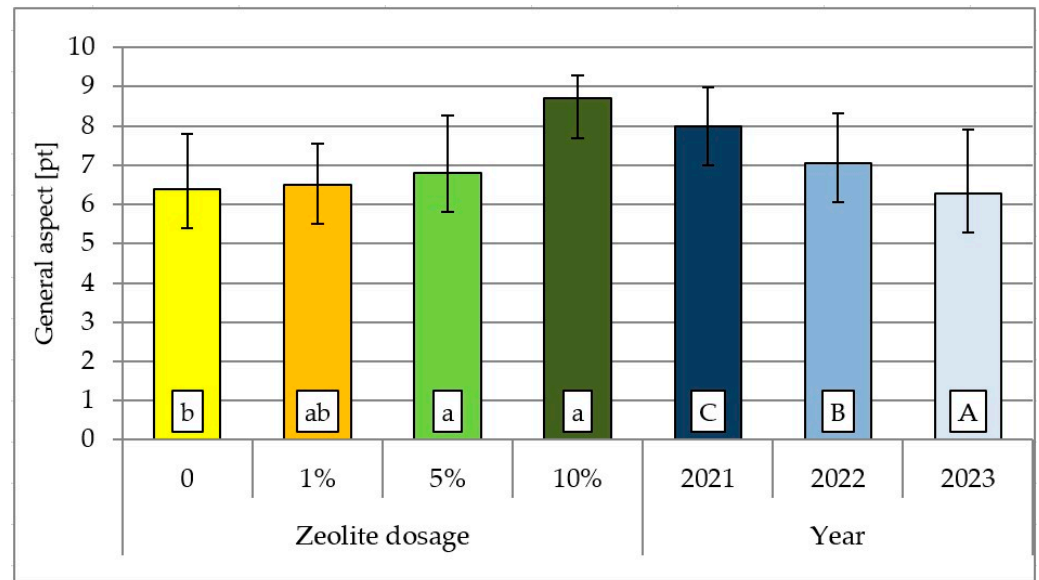


Figure 8. Overall visual quality of turf depending on zeolite dose and years of use (mean of 2021–2023). Values represent means of replications and years. Error bars show standard deviation. Bar colors indicate zeolite doses (0%, 1%, 5%, 10%) and years of use (2021, 2022, 2023). Different lowercase letters indicate significant differences between zeolite doses, and uppercase letters indicate differences between years (Tukey’s HSD test, $p \leq 0.05$).

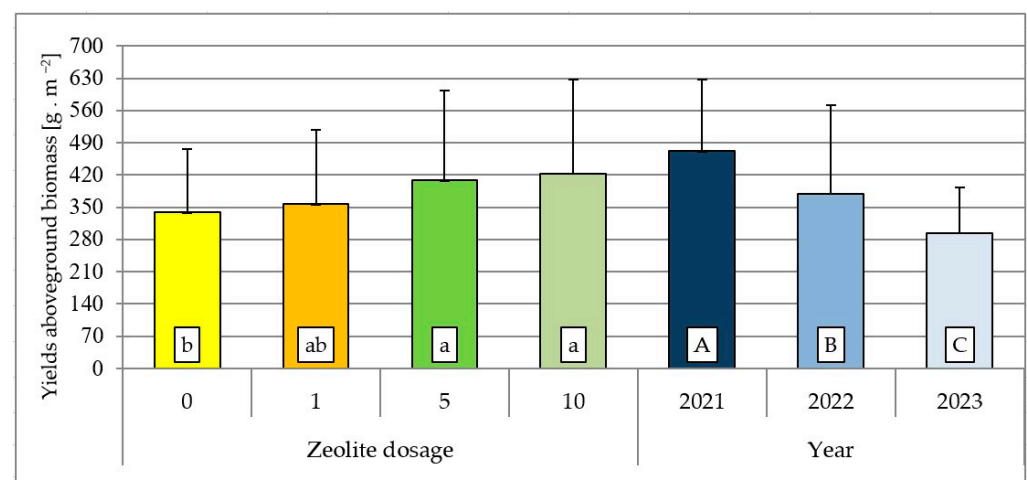


Figure 9. Aboveground biomass yield in relation to zeolite dose and years of lawn turf use (mean of 2021–2023). Values represent means of replications and years. Error bars show standard deviation. Bar colors indicate zeolite doses (0%, 1%, 5%, 10%) and years of use (2021, 2022, 2023). Different lowercase letters indicate significant differences between zeolite doses, and uppercase letters indicate differences between years (Tukey’s HSD test, $p \leq 0.05$).

Across the three experimental years, zeolite addition generally tended to increase turf biomass yields compared with the control (0%), with the clearest and statistically significant effects observed in 2021 and 2022, particularly at the 5% and 10% doses. In 2021, which was characterized by the highest overall yields, zeolite at 5% increased yield by 23.6% compared with the control, while the 10% dose resulted in a 25.4% increase. A similar trend persisted

in 2022, when control yields were $326.7 \text{ g} \cdot \text{m}^{-2}$, and the 10% zeolite addition led to an increase of more than 30%. In 2023, overall yields declined markedly, and no statistically significant differences were found among treatments; however, the highest mean yield was still observed at the 10% dose ($325 \text{ g} \cdot \text{m}^{-2}$) (Figure 10).

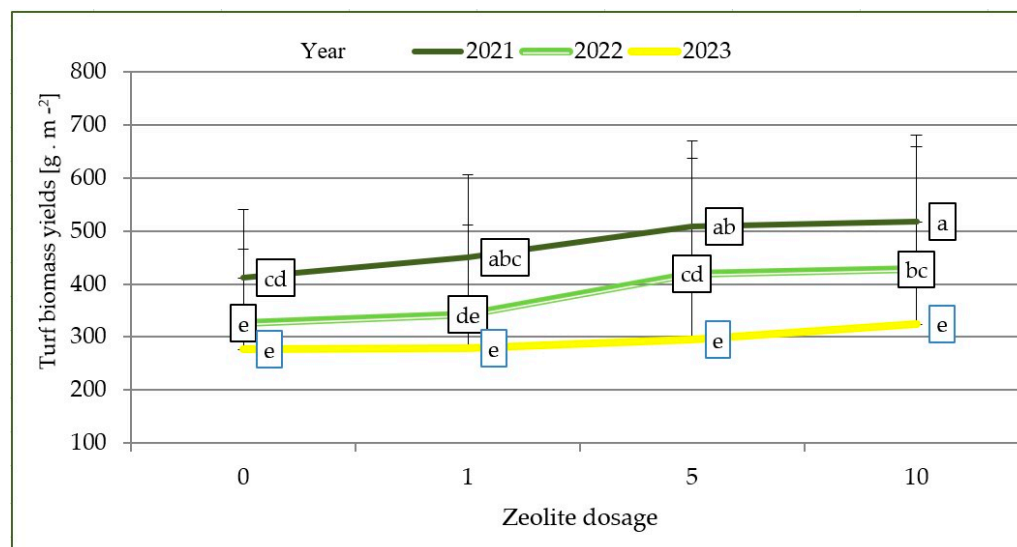


Figure 10. Effect of different zeolite doses on turf biomass yields across successive years of use (mean of 2021–2023). Values represent means of replications and years. Error bars show standard deviation. Different letters indicate significant differences between groups (Tukey’s HSD test, $p \leq 0.05$).

Data analysis indicates that the 5% dose is close to optimal, since further increasing to 10% provides only a slight additional yield increase, which may not offset the higher cost of zeolite application. The 1% dose showed a moderate effect, suggesting that it may be insufficient under field conditions. Based on these results, zeolite application at 5% can be recommended, especially on sites requiring improved soil structure and enhanced water retention, both of which support more efficient grass growth.

3.2.5. Winter Survival of Plants

Application of zeolite at 5% and 10% significantly improved winter survival of turfgrass plants, with mean ratings approaching 9.0 (Figure 11). Year of use was also a significant factor, with lower survival observed after the winter of 2023 (on average by 0.7 points). The absence of a dose $\times$ year interaction confirms the stable effect of zeolite as a factor enhancing winter hardiness. In 2022 (a mild winter), all treatments showed good survival. In 2023 (a season characterized by temperature fluctuations and limited snow cover), only higher zeolite doses effectively reduced turf damage (Tables 1 and S1).

The data indicate that zeolite addition to the substrate positively influenced grass winter survival in both study years. In 2022, winter survival in the control (0%) was rated at 8.26, while increasing the zeolite dose to 10% raised the rating to 9.00 (an improvement of about 9%). A similar trend was observed in 2023, where the best survival was again recorded at the 10% dose (8.47) compared with the control (7.41) (Tables 1 and S1).

The greatest improvements compared with the control were observed at the 5% and 10% doses, with effectiveness increasing as zeolite dose rose. The 1% dose had only a moderate effect (3% increase in 2022 and 2023), suggesting it is less effective. Differences between 5% and 10% were smaller, which may indicate that the 5% dose provides most of the possible benefit for winter survival, while a higher dose adds only a limited advantage.

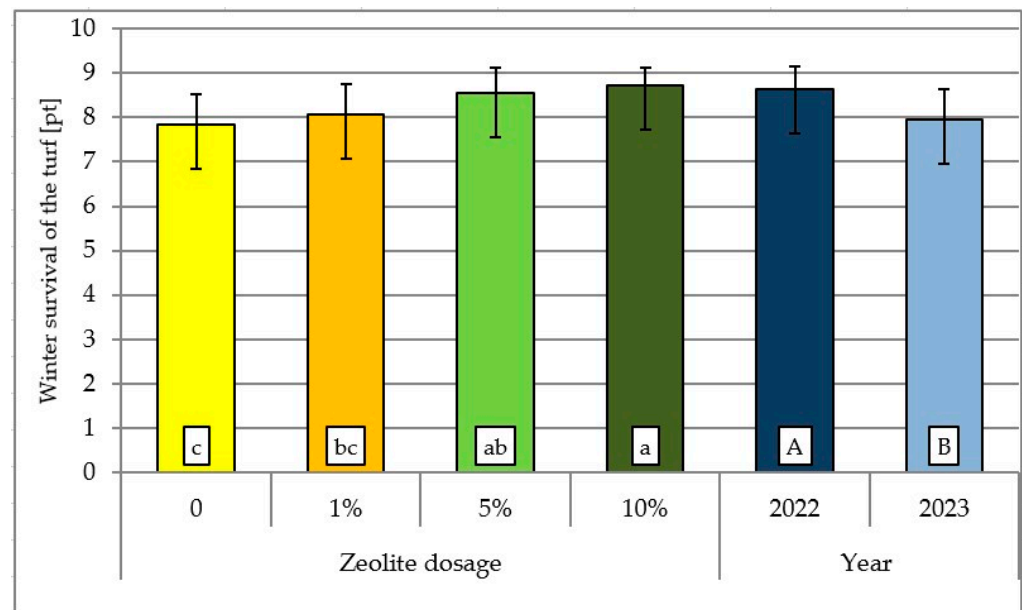


Figure 11. Winter survival of lawn turf plants in relation to zeolite dose and years of use (mean of 2021–2023). Values represent means of replications and years. Error bars show standard deviation. Bar colors indicate zeolite doses (0%, 1%, 5%, 10%) and years of use (2021, 2022, 2023). Different lowercase letters indicate significant differences between zeolite doses, and uppercase letters indicate differences between years (Tukey’s HSD test, $p \leq 0.05$).

4. Discussion

Zeolites are widely used as soil amendments and components of slow-release fertilizers [20,21]. Numerous studies have also demonstrated their beneficial effects on plant growth and development [8,22,23]. This effect is thought to result primarily from long-term improvements in soil physicochemical properties induced by zeolite. These minerals are characterized by exceptionally high cation exchange capacity, large specific surface area, and porous structure, which together enhance water retention and nutrient use efficiency [24]. Among the roughly 40 known types of natural zeolites, clinoptilolite is the most abundant, cheapest, and most commonly applied [25]; it was therefore selected for use in this study.

Our results showed that zeolite addition to the substrate had a positive effect on seedling emergence, growth, and biomass production of grasses, although responses differed between species. *Lolium perenne*, a demanding species sensitive to water deficit, responded most strongly to the 5% zeolite dose, confirming earlier observations that nutrient and moisture availability are critical factors for its growth [26–28]. *Festuca rubra*, more tolerant to environmental stress, benefited most from the 10% dose, which can be attributed to its ability to utilize resources more steadily and to its root system’s high exploratory capacity [29]. At the physiological level, *F. rubra* has been reported to accumulate more proline and activate antioxidant enzymes, increasing its resistance to drought stress [26]. This species also produced greater root biomass than *L. perenne*, confirming its better adaptability to changes in soil structure and fertility. Similar differences in grass responses to zeolite application have been reported by other authors [30,31].

Enriching soil substrate with zeolite also improved the utility traits of lawn turf by increasing turf density (ground cover) and reducing the proportion of dicotyledonous weeds, which diminish turf aesthetic and functional value. Similar findings were reported by Mondal et al. [23] and Cataldo et al. [20], who showed that zeolite as a fertilizer additive increased the proportion of grasses (better turf cover) and simultaneously reduced weeds in the sward. According to these authors, zeolites, by enhancing nutrient and water retention

in the root zone, support cultivated plant species (which absorb them faster), thereby limiting resource availability to slower-growing dicotyledonous weeds, giving grasses a competitive advantage. The role of zeolites in limiting nutrient availability to weeds while promoting grass development has also been emphasized by Reháková et al. [32]. This mechanism is believed to be associated with the high cation exchange capacity (CEC) and porous structure of zeolites, which enable water and nutrient ion binding [24,33].

Zeolite also had a positive impact on turf aesthetic qualities (overall aspect), particularly in the first year after application. In subsequent years, the effect weakened, although the highest doses (10%) still provided a buffering function, protecting turf under water and heat stress. Similar observations were reported by Martelletti et al. [34], who emphasized the short-term nature of a single application and the need for repeated treatments over extended use. It was also noted that zeolite increased turf resistance to environmental stresses, including drought and frost, as reflected in winter survival results. Application of 5% and 10% doses significantly improved survival, particularly under harsher winter conditions (2023). This mechanism can be explained by improved water retention, stabilization of thermal conditions, and soil microstructure, particularly in light soils [15,35]. Similar findings were reported by Li et al. [36] in the context of degraded soil reclamation, where zeolite improved water–air balance, reduced plant water and heat stress, and increased tolerance to extreme environmental conditions.

The three-year analysis of aboveground biomass yields revealed that the positive effect of zeolite varied among years, being most evident in the first two years of this study. The highest values were obtained at 5% and 10% doses, which increased yield by 20–30% relative to the control. This effect was particularly pronounced in years with favorable weather (2021–2022), whereas under harsher conditions (2023) higher doses played a stabilizing role. Similar relationships were described by Farzam et al. [37] and Mondal et al. [23], who pointed out that zeolite, by improving water retention and sorption capacity, can increase plant productivity in a manner comparable to controlled-release fertilizers. The optimal yield effect at the 5% dose suggests that further increases provide no proportional benefits. These findings are consistent with Fugoni [38], who emphasized the need to balance agronomic effects with application costs.

From the perspective of horticultural practice and green space management, the optimal zeolite dose lies in the 5–10% range, as demonstrated under both laboratory and field conditions. However, the 5% addition appears most justified in terms of efficiency and cost-effectiveness. The higher 10% dose provides an additional protective effect under stress conditions but only a small incremental increase in yield and aesthetic quality, which in practice may not offset the higher material costs. Similar findings were reported by Kakabouki et al. [33] in maize, where the optimal dose was $7.5 \text{ t} \cdot \text{ha}^{-1}$, while higher applications did not improve yield or nitrogen use efficiency. These authors suggest that in agricultural use of zeolite there is a threshold of effectiveness, beyond which further increases bring no additional yield benefits and may sometimes even have adverse effects. Fugoni [38] and Kavvadias et al. [25] likewise note that the positive effects of zeolite become marginal beyond the optimal range ($5\text{--}7.5 \text{ t} \cdot \text{ha}^{-1}$), while raw material costs become less profitable at large scales, such as sports fields or recreational areas. Farzam et al. [37] reached similar conclusions, emphasizing the need to balance soil improvement with the economic feasibility of zeolite application. Considering both literature data and our own results, zeolite dosing should be tailored to the species—moderate for intensive species such as *L. perenne* and higher for more stress-tolerant and stable species such as *F. rubra*.

Our findings also indicate that the positive effect of zeolite (particularly at lower doses) on grass development and turf utility weakens over successive years of use. By the third year, the effect remained noticeable but was markedly reduced, suggesting a gradual

decline in sorption properties due to saturation of exchange sites [8]. The strongest effect is usually observed in the first year, less often in the first two seasons after application, as also confirmed by Szatanik-Kloc et al. [39] and Nakhli et al. [22]. This phenomenon is attributed both to leaching of the mineral from the root zone and to progressive saturation of its sorption capacity. Consequently, although effective, zeolite action is limited in duration and may require reapplication for longer-term turf management. Similar observations were made by Reháková et al. [32], and Martelletti et al. [34]. In their studies, zeolite significantly improved soil properties—including cation exchange capacity and water retention—which in the first season translated into enhanced plant growth. However, in subsequent years, its effect was much reduced or negligible, with weather conditions, soil preparation, and interspecific interactions exerting stronger influence on turf dynamics and seedling growth. According to Szatanik-Kloc et al. [39], the limited durability of zeolite action also results from its low concentration in soil. The authors stressed that at a dose of $8 \text{ t} \cdot \text{ha}^{-1}$, the zeolite share in soil mass was only about 0.35%, insufficient to maintain long-term changes in pH, cation exchange capacity, or water retention. Nakhli et al. [22] likewise pointed out that zeolite-induced physicochemical effects—such as improved water-holding capacity or nutrient sorption—are often short-lived after a single application. Therefore, to sustain favorable soil properties and stable plant yields, strategies of repeated or supplemental zeolite application are necessary, particularly in intensively used soils.

From a practical perspective, the results confirm the usefulness of zeolite as a component that improves grass growth conditions and supports the maintenance of dense, resilient, and aesthetically valuable turf. This may be particularly beneficial on poorer soils, where improved water retention and water–air balance are crucial for turf development, persistence, and reduction of plant stress [35]. Zeolite can therefore be regarded both as a tool for adapting lawns to climate change and as a means of reducing costs and environmental pressure in urban green space management [20,30]. At the same time, it should not be considered a universal solution, but rather as an element of broader, integrated water and nutrient management systems.

The results of the present study confirm that a universal approach to zeolite application is not advisable—its effectiveness depends both on habitat conditions and on the physiological and morphological traits of a given species. These findings provide a solid basis for further research into the long-term impact of zeolites on lawns, including their potential combination with other management techniques to achieve more durable effects. An interesting aspect worth highlighting is the possible interaction between zeolite and the soil microbiome. Research by Kavvadias et al. [25] indicates that zeolite presence may promote the development of beneficial microorganisms (e.g., *Pseudomonas*, *Azotobacter*), which support plant growth and improve phosphorus availability. This represents a promising direction for further studies, particularly in the context of developing sustainable lawn care technologies in urban environments. The application of zeolite in turfgrass mixtures remains a rarely addressed research area, thus the results presented here provide new empirical data and may serve as a starting point for further analyses.

5. Conclusions

The use of zeolite as a soil substrate additive significantly improves the growth and development of turfgrass cultivars as well as the functional and aesthetic traits of lawn turf. This effect is evidenced by higher seedling emergence, increased aboveground and root biomass yields, and enhanced turf quality, including better visual appearance, denser turf cover, and improved winter hardiness compared with non-zeolite conditions. The most beneficial effects were observed at 5% and 10% zeolite doses, with 5% identified as the optimal rate. This level ensured clear yield increases, better turf cover, and a

reduced share of dicotyledonous species while providing comparable results to the 10% dose but with lower material input. Turfgrass species responded differently to zeolite application. These differences were reflected in plant height and in the production of both aboveground and belowground biomass. *Lolium perenne* reacted more dynamically to the improved soil water–air conditions provided by zeolite, whereas *Festuca rubra* exhibited greater growth stability and made more effective use of higher zeolite doses in root development. The positive influence of zeolite persisted over time, although its efficiency gradually decreased in subsequent years of turf use. The strongest impact was recorded in the first year after application, but even after three years, zeolite continued to positively affect turf performance and utility traits. In addition, zeolite increased turf resistance to environmental stresses such as drought and frost, as demonstrated by higher overall aspect ratings and improved winter survival, particularly at higher doses. Therefore, zeolite can be recommended as an ecological soil amendment that enhances soil water–air relations and supports effective and sustainable management of green spaces, especially in low-fertility soils.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15112554/s1>, Table S1: Effect of different zeolite doses on selected turf performance parameters over three years of lawn use.

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