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Growth and Nutrients Uptake of Creeping Bentgrass (*Agrostis stolonifera* L.) Applying Compound Fertilizer Containing Amino Acids

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Abstract: This study was conducted to evaluate the effects of a compound fertilizer containing amino acids (CFAA) on the growth and quality of creeping bentgrass (*Agrostis stolonifera* L.) and to investigate nutrients uptake. Treatments were as follow. No fertilizer treatment (NF), control (compound fertilizer 3 active ingredient nitrogen g/m^2), CFAA-1 (control+1 mL/m^2), CFAA-2 (control+2 mL/m^2), and CFAA-3 (control+4 mL/m^2). Changes in soil properties following CFAA application were negligible, indicating minimal alteration of soil chemical properties. Compared to the untreated control, CFAA treatments exhibited increases in growth and quality parameters, including turf color index, chlorophyll a+b content, shoot height, clipping yield, and shoot and root dry weights, as well as nutrient content and uptake such as nitrogen, phosphorus, and potassium. Significant positive correlations ($p \leq 0.01$) were observed between CFAA application rates and growth parameters, as well as nutrients uptake. These results indicate that CFAA application enhances nitrogen uptake, which is associated with increased chlorophyll a+b content and biomass production, ultimately contributing to improved turfgrass growth and quality.

Keywords: Chlorophyll content, Clipping yield, Creeping bentgrass, Compound fertilizer containing amino acids (CFAA), Nitrogen uptake

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Introduction

Creeping bentgrass (*Agrostis stolonifera* L.) is widely used for high-quality turf management such as golf course greens due to its high shoot density, fine leaf texture, and excellent visual quality [1]. However, maintaining optimal growth and quality of creeping bentgrass requires intensive management, and environmental stress conditions such as high temperature and drought during the summer season frequently cause growth decline [2,3]. These stress conditions inhibit nutrient uptake and reduce chlorophyll content, ultimately leading to decreased turf growth and quality [4].

Nitrogen (N) is one of the most important nutrients for turfgrass growth, playing a key role in chlorophyll synthesis, photosynthesis, and biomass accumulation [5].

Therefore, efficient N uptake is essential for maintaining turf quality [6]. Conventional fertilization methods widely used to supply nutrients may have limited efficiency under adverse environmental conditions, and excessive fertilization can cause nutrient leaching and degradation of soil conditions, resulting in environmental problems [7]. Consequently, there is growing interest in alternative or supplementary fertilization strategies that enhance nutrient use efficiency while minimizing environmental impact [8].

Recently, amino acids-based fertilizers have attracted attention as promising agents for promoting plant growth and improving stress tolerance [9]. Amino acids are directly absorbed by plants and act as precursors for protein synthesis and metabolic processes, enhancing nutrient uptake and physiological activities [9]. Previous studies have reported that amino acids treatments contribute to increased chlorophyll content, promotion of both shoot and root growth, and enhanced tolerance to abiotic stress [10]. However, research on the effects of compound fertilizers containing amino acids on turf growth, nutrient dynamics, and the interrelationships among growth indices is still insufficient.

Understanding the relationship between turf growth characteristics and nutrient uptake is crucial for establishing efficient fertilization strategies and improving turf management techniques. In particular, elucidating the effects of amino acids-based fertilizers on nitrogen uptake and the resulting changes in turf growth and quality holds significant implications for sustainable turf management. Therefore, this study was conducted to investigate the effects of a compound fertilizer containing amino acids (CFAA) on the growth and quality of creeping bentgrass (*A. stolonifera* L.), and to analyze the interrelationships among various growth indices to clarify the growth characteristics.

Results and Discussion

Soil chemical properties

After the completion of the experiment, soil pH, electrical conductivity (EC), organic matter (OM), total nitrogen (T-N), available phosphorus (Av.-P_2O_5), and exchangeable potassium (Ex-K) ranged from 7.12 to 7.18, 0.18 to 0.26 dS/m, 0.20 to 0.24%, 0.007 to 0.014%, 37.1 to 64.1 mg/kg, and 0.10 to 0.16 cmol$_c$/kg, respectively (Table 1). Compared to the NF treatment, the CFAA treatment groups increased T-N, Av.-P_2O_5, and Ex-K levels; however, there were no statistically significant differences compared to the control. OM content in CFAA treatments were increased than that of NF, and in only CFAA-3 treatment than control. The correlation analysis between CFAA application rates and soil parameters showed no statistically significant relationships. These results indicate that CFAA application had minimal impact on soil chemical properties. This finding aligns with Lee et al. [11], who reported minimal changes in soil chemical properties following amino acids treatment during maize (*Zea mays* L.) cultivation.

Table 1. Chemical properties of soil used before and after in this study

Treatments[1)]	pH	EC	OM	T-N	Av.-P_2O_5	Ex-K
	(1:5)	dS/m	%		mg/kg	cmol$_c$/kg
NF	7.18a[2)]	0.18a	0.20c	0.007b	37.2b	0.10b
Control	7.13ab	0.24a	0.21bc	0.013a	56.0a	0.16a
CFAA-1	7.12ab	0.25a	0.22b	0.014a	64.1a	0.16a
CFAA-2	7.14ab	0.25a	0.23ab	0.014a	58.7a	0.16a
CFAA-3	7.12ab	0.26a	0.24a	0.014a	61.4a	0.16a
Correlation[3)]	-0.033	0.451	0.771**	0.388	0.106	-0.170

[1)]Treatments were follows. NF: no fertilizer, control (compound fertilizer; N-P_2O_5-K_2O=10-5-30, 3 N a.i. g/m^2/4-week), CFAA-1 (control+ CFAA 1 mL/m^2/time), CFAA-2 (control+ CFAA 2 mL/m^2/time), and CFAA-3 (control+ CFAA 4 mL/m^2/time). Compound fertilizer dissolved with tap water were applied every 4 weeks since July 11, 2024, and CFAA applied it every week. CFAA means a compound fertilizer containing amino acids.
[2)]Means with the same letters within a column are not significantly different by Duncan's multiple range test $p \le 0.05$ level.
[3)NS] represent no significance by Pearson's correlation coefficient between CFAA application rate and soil factor. It was analyzed between control group and CFAA treatment groups.

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Quality and growth of creeping bentgrass applying CFAA

After CFAA treatments, the turfgrass exhibited a turf color index (TCI) ranging from 6.36 to 7.40, which was increased compared to the NF group, with the increase becoming significant from September onwards when compared to the control (Table 2). Correlation analysis between CFAA application rates and TCI showed a positive correlation throughout the entire growing period ($p \le 0.01$). Chang et al. [11] reported that amino acids liquid fertilizers promote the TCI in turfgrass, supporting the findings of this study.

The chlorophyll a+b content in the CFAA treatment groups ranged from 1,820 to 2,757 μg/g. Compared to the NF treatment, chlorophyll levels increased by more than 14.1% from August onwards, and relative to the control, increases of over 8.9% were observed from September (Table 2). The average chlorophyll a+b content measured throughout the experimental period was 11.8 to 14.8% higher in the CFAA treatments than in the control. A significant positive correlation ($p \le 0.01$) was observed between CFAA application rates and chlorophyll a+b content. Amino acids fertilizer application is known to increase chlorophyll content in turfgrass [13].

In CFAA treatments, shoot height of creeping bentgrass ranged from 3.42 to 8.59 cm (Table 2). Compared to the NF group, shoot height increased by more than 14.2% from July onwards, and it was at least 2.7% higher than the control group. When comparing the average values measured during the entire growing period after the experiment, shoot height increased by 28.1 to 50.0% compared to the NF treatment and by 11.3 to 17.0% compared to the control. A significant positive correlation ($p \le 0.01$)

Table 2. Growth and quality of the creeping bentgrass applying a compound fertilizer containing amino acid (CFAA)

Treatment[1)]	July	August	September	October	November	December	January	February	March	Average
Turf color index (scale 1-9, 1=worst, 6=acceptable, 9=best)										
NF	6.76c[2)]	6.80c	6.37d	6.81e	6.53e	6.49d	6.36d	6.21e	6.32e	6.52
Control	7.25b	7.16b	6.87c	6.87d	6.92d	6.72c	6.48c	6.36d	6.41d	6.78
CFAA-1	7.35ab	7.27ab	7.02b	7.18c	7.22c	7.10b	7.00b	6.67c	6.82c	7.07
CFAA-2	7.35ab	7.30a	7.02b	7.23b	7.27b	7.14a	7.08a	6.69ab	6.87ab	7.10
CFAA-3	7.40a	7.37a	7.10a	7.27a	7.30a	7.15a	7.09a	6.70a	6.91a	7.14a
Correlation[3)]	0.688**	0.747**	0.875**	0.807**	0.798**	0.747**	0.757**	0.739**	0.781**	0.802**
Chlorophyll a+b content (μg/g, FW)										
NF	2,303a	2,085c	2,054c	1,820d	1,930e	1,890d	-	-	-	2,014d
Control	2,432a	2,284b	2,151b	2,240c	2,384d	2,428c	2,303d	1,910c	2,048c	2,242c
CFAA-1	2,418a	2,397ab	2,344a	2,482b	2,663c	2,657b	2,613c	2,515b	2,479b	2,507b
CFAA-2	2,417a	2,418ab	2,346a	2,548a	2,716ab	2,688ab	2,648b	2,569ab	2,541ab	2,543ab
CFAA-3	2,424a	2,436a	2,352a	2,579a	2,757a	2,737a	2,678a	2,606a	2,600a	2,574a
Correlation	-0.022^{NS}	0.538*	0.623**	0.819**	0.824**	0.836**	0.781**	0.750**	0.810**	0.795**
Shoot height (cm)										
NF	5.98e	4.67d	4.57d	4.03d	4.03d	4.02d	3.62c	3.42c	3.53c	4.21e
Control	8.17d	5.34c	5.24c	5.36c	5.60c	5.59c	4.67b	3.91b	4.65b	5.39d
CFAA-1	8.39c	5.56bc	5.64b	5.87b	5.87b	5.90b	5.74a	5.43a	5.62a	6.00c
CFAA-2	8.46b	5.73b	5.67b	5.92b	6.05a	6.05a	5.81a	5.49a	5.67a	6.09b
CFAA-3	8.59ab	6.15a	6.30a	6.18a	6.25a	6.18a	5.84a	5.54a	5.75a	6.31a
Correlation	0.909**	0.886**	0.945**	0.893**	0.879**	0.867**	0.713**	0.706**	0.724**	0.880**

[1)]Treatments were follows. NF: no fertilizer, control (compound fertilizer; N-P_2O_5-K_2O=10-5-30, 3 N a.i. g/m^2/4-week), CFAA-1 (control+ CFAA 1 mL/m^2/time), CFAA-2 (control+ CFAA 2 mL/m^2/time), and CFAA-3 (control+ CFAA 4 mL/m^2/time). Compound fertilizer dissolved with tap water were applied every 4 weeks since July 11, 2024, and CFAA applied it every week. CFAA means a compound fertilizer containing amino acids.
[2)]Means with the same letters within a column are not significantly different by Duncan's multiple range test $p \le 0.05$ level.
[3)]NS, * and ** represent no significance, a significance at the 0.05 and 0.01 probability level by Pearson's correlation coefficient between CFAA application rate and growth factors such as turf color index, chlorophyll a+b content, and shoot height. It was analyzed between control group and CFAA treatment groups.

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Agric. Environ. Sci. 2026, 45, 115-124

was found between CFAA application rates and shoot height. Amino acid applications are reported to enhance turf density and shoot growth, which aligns with the increased turf growth observed in this study [14].

Clipping yield of creeping bentgrass applying CFAA

During the experimental period following CFAA treatment, the total clipping yield of creeping bentgrass ranged from 16.1 to 206.9 g/m² (Table 3). Compared to the NF, this represented an increase of 832 to 1,181%, and compared to the control plot, an increase of 126.4 to 177.4%. Correlation analysis between CFAA application rates and turf fresh biomass showed a significant positive correlation ($p \leq 0.01$), indicating that CFAA treatment promotes an increase in turf fresh biomass and enhances growth. Zhang et al. [13] reported that amino acid treatment enhances turf resistance to heat and drought stress, resulting in increased turf clipping, which aligns with the findings of this study. In the current study, turf biomass also increased following amino acid fertilizer application during the high-temperature seasons of July and August.

After the completion of the experiment, the root length, shoot dry weight, root dry weight, and T/R ratio of the turfgrass were measured (Table 4). The root length in the CFAA-treated plots ranged from 10.7 to 22.6 cm, representing increases of 38.7 to 112.0% compared to the NF treatment and 37.3 to 52.9% compared to the control. Shoot dry weight ranged from 496.6 to 953.6 g/m^2, showing increases of 66.5 to 92.0% relative to NF and 14.1 to 15.3% relative to the control. Root dry weight ranged from 310.5 to 566.7 g/m^2, with increases of 57.5 to 82.5% compared to NF and 13.2 to 15.9% compared to the control. The T/R ratio ranged from 1.60 to 1.73, with no statistically significant differences observed between the CFAA, NF, and control treatments.

Correlation analysis revealed a positive relationship between CFAA application rates and root length, shoot dry weight ($p \leq 0.01$), as well as root dry weight ($p \leq 0.05$), indicating that amino acid fertilizer promotes root growth and turf growth in creeping bentgrass. This aligns with findings by Mertz et al. [14], who reported increased root growth in turfgrass following amino acid treatment. As root growth enhances nutrient and water uptake, it contributes to improved turf growth, quality, and resistance to environmental stress [13].

Nutrient content and uptake in the creeping bentgrass applying CFAA

The nutrient content and uptake in turfgrass foliage after CFAA treatment were investigated (Table 5). At the end of the experiment, the contents of nitrogen, phosphorus, and potassium in the turfgrass foliage ranged from 0.84 to 3.57%, 0.21 to 0.29%, and 1.15 to 2.15%, respectively. Compared to the NF treatment, these values increased by 233.3 to 325.0%, 11.7 to 39.4%, and 59.4 to 86.2%, respectively. When compared to the control, the CFAA-2 and CFAA-3 treatments showed increases of 18.1 to 27.5%,

Table 3. Clipping yield of the creeping bentgrass applying a compound fertilizer containing amino acid (CFAA)

Treatment[1)]	Clipping yield (g/m^2)									
	July	August	September	October	November	December	January	February	March	Total
NF	5.4b[2)]	3.1e	2.5e	1.3e	1.3e	1.3e	1.3e	-	-	16.1e
Control	29.2a	11.7d	10.8d	12.3d	14.9d	16.2d	9.4d	5.9c	8.4d	104.6d
CFAA-1	34.3a	15.4cd	18.4c	22.6c	27.1c	27.1c	21.6	14.6b	19.1c	166.7c
CFAA-2	34.0a	21.3ab	23.5b	25.6b	33.5b	29.2b	25.2b	16.8a	21.1b	192.3b
CFAA-3	31.4a	23.0a	30.6a	28.6a	35.6a	31.1a	26.5a	18.4a	23.3a	206.9a
Correlation[3)]	0.073^{NS}	0.804**	0.965**	0.878**	0.869**	0.819**	0.814**	0.830**	0.834**	0.870**

1)Treatments were follows. NF: no fertilizer, control (compound fertilizer; N-P_2O_5-K_2O=10-5-30, 3 N a.i. g/m^2/4-week), CFAA-1 (control+ CFAA 1 mL/m^2/time), CFAA-2 (control+ CFAA 2 mL/m^2/time), and CFAA-3 (control+ CFAA 4 mL/m^2/time). Compound fertilizer dissolved with tap water were applied every 4 weeks since July 11, 2024, and CFAA applied it every week. CFAA means a compound fertilizer containing amino acids.
2)Means with the same letters within a column are not significantly different by Duncan's multiple range test $p \leq 0.05$ level.
3)NS and ** represent no significance and a significance at the 0.01 probability level by Pearson's correlation coefficient between CFAA application rate and clipping yield. It was analyzed between control group and CFAA treatment groups.

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Agric. Environ. Sci. 2026, 45, 115-124

Table 4. Root length and dry weight of shoot and root in the creeping bentgrass applying a compound fertilizer containing amino acid (CFAA)

Treatments[1)]	Root length (cm)	Shoot and root dry weight (g/m^2)		T/R ratio (g/g)
		Shoot	Root	
NF	10.7d[2)]	496.6c	310.5c	1.60a
Control	14.8c	826.8b	489.0b	1.69a
CFAA-1	20.3b	943.6a	553.4a	1.71a
CFAA-2	21.1ab	953.5a	566.7a	1.69a
CFAA-3	22.6a	950.9a	557.5a	1.71a
Correlation[3)]	0.667**	0.649**	0.531*	-0.058^{NS}

[1)]Treatments were follows. NF: no fertilizer, control (compound fertilizer; N-P_2O_5-K_2O=10-5-30, 3 N a.i. g/m^2/4-week), CFAA-1 (control+ CFAA 1 mL/m^2/time), CFAA-2 (control+ CFAA 2 mL/m^2/time), and CFAA-3 (control+ CFAA 4 mL/m^2/time). Compound fertilizer dissolved with tap water were applied every 4 weeks since July 11, 2024, and CFAA applied it every week. CFAA means a compound fertilizer containing amino acids.
[2)]Means with the same letters within a column are not significantly different by Duncan's multiple range test $p \leq 0.05$ level.
[3)]NS, * and ** represent no significance, a significance at the 0.05 and 0.01 probability level by Pearson's coefficient between CFAA application rate and root length or partial dry weight, respectively. It was analyzed between control group and CFAA treatment groups.

Table 5. Nutrient contents and uptake in the creeping bentgrass applying a compound fertilizer containing amino acid (CFAA)

Treatments[1)]	Nutrient content (%)			Nutrient uptake (g/m^2)		
	N	P	K	N	P	K
NF	0.84d[2)]	0.21c	1.15c	0.14e	0.03d	0.18d
Control	2.80c	0.23b	1.84b	2.93d	0.24c	1.92c
CFAA-1	3.31b	0.28a	2.13a	5.51c	0.46b	3.56b
CFAA-2	3.40ab	0.29a	2.15a	6.53b	0.55a	4.12a
CFAA-3	3.57a	0.29a	2.12a	7.39a	0.60a	4.39a
Correlation[3)]	0.811**	0.670**	0.606**	0.881**	0.858**	0.845**

[1)]Treatments were follows. NF: no fertilizer, control (compound fertilizer; N-P_2O_5-K_2O=10-5-30, 3 N a.i. g/m^2/4-week), CFAA-1 (control+ CFAA 1 mL/m^2/time), CFAA-2 (control+ CFAA 2 mL/m^2/time), and CFAA-3 (control+ CFAA 4 mL/m^2/time). Compound fertilizer dissolved with tap water were applied every 4 weeks since July 11, 2024, and CFAA applied it every week. CFAA means a compound fertilizer containing amino acids.
[2)]Means with the same letters within a column are not significantly different by Duncan's multiple range test $p \leq 0.05$ level.
[3)]** represent a significance at the 0.01 probability level by Pearson's coefficient between CFAA application rate and nutrient content or uptake amount, respectively. It was analyzed between control group and CFAA treatment groups.

19.6 to 24.8%, and 15.8 to 16.8%, respectively. Correlation analysis revealed significant positive correlations ($p \leq 0.01$) between CFAA application rates and nitrogen, phosphorus, and potassium contents in the turfgrass tissue.

During the experimental period, the amounts of absorbed nitrogen, phosphorus, and potassium were 0.14 to 8.88 g/m^2, 0.03 to 0.72 g/m^2, and 0.18 to 5.28 g/m^2, respectively. Compared to NF, nitrogen uptake increased by 2,341 to 6,417%, phosphorus by 713 to 2,023%, and potassium by 1,079 to 2,755%. Compared to the control, nitrogen, phosphorus, and potassium uptakes increased by 99.2 to 167.0%, 101.6 to 161.2%, and 96.1 to 142.1%, respectively. Positive correlations ($p \leq 0.01$) were observed between CFAA application and the uptake of nitrogen, phosphorus, and potassium.

The application of amino acids is known to enhance nitrogen uptake through direct absorption by plants [15]. Increased nitrogen uptake is reported to stimulate the absorption of other nutrients such as phosphorus and potassium [16], contributing to enhanced turf growth and quality [17].

Path analysis for CFAA application in the creeping bentgrass

The present study confirmed positive correlations between CFAA application rates and various growth parameters, including TCI, chlorophyll a+b content, shoot height, fresh biomass, shoot dry weight, root dry weight, and nutrient uptake (Tables 2–5). To evaluate the relative importance of factors affecting turf growth and development, partial correlation analysis was performed,

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Agric. Environ. Sci. 2026, 45, 115-124

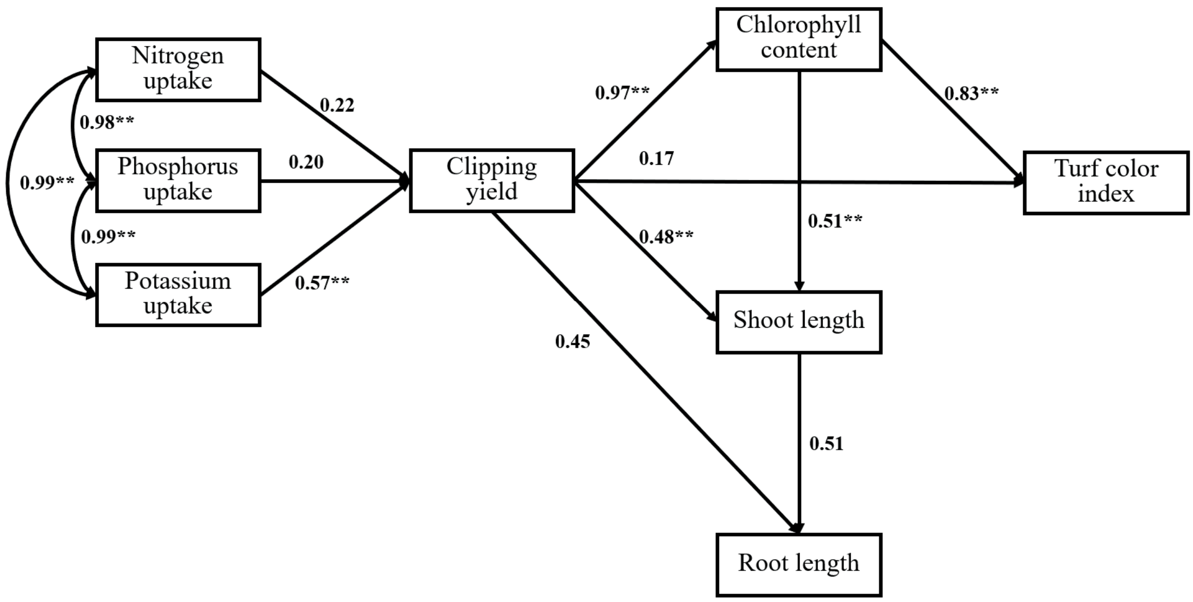

Fig. 1. Path analysis of growth of factors in the creeping bentgrass treated with a compound fertilizer containing amino acid (CFAA). The values were a standardized estimate, and ** represent a significance at the 0.01 probability level. Observed endogenous variables are clipping yield, chlorophyll content, turf color index, shoot length, and root length, and observed exogenous variables nitrogen uptake, phosphorus uptake, and potassium uptake. χ^2 statistic: 15.282 (df=15, *p*=0.432), RMSEA (Root Mean Square Error of Approximation): 0.035, CFI (Comparative Fit Index): 0.999, TLI (Tucker-Lewis Index): 0.999, NFI (Normed Fit Index): 0.961.

followed by path analysis among growth indices measured after CFAA treatment (Fig. 1).

CFAA application significantly increased nitrogen, phosphorus, and potassium uptake in turfgrass (Table 5). Amino acids supplied through CFAA can be directly absorbed by plants and utilized as precursors for the synthesis of various metabolic compounds [18]. In addition, amino acid application has been reported to enhance nitrogen uptake efficiency [19]. The resulting improvement in nutrient acquisition, particularly nitrogen uptake, is likely a major factor underlying the enhanced growth responses observed in turfgrass [20]. Nitrogen absorbed by turfgrass is incorporated into protein synthesis; a portion of which contributes to the synthesis of chlorophyll-associated proteins, thereby increasing chlorophyll content [13]. These findings are consistent with those of Chang et al. [12], who reported that nitrogen supply enhances turf visual quality and promotes early spring growth. Amino acid application promotes nitrogen absorption, thereby enhancing turf growth and development; notably, increased nitrogen uptake stimulates the absorption of phosphorus and potassium, which are essential nutrients for turfgrass growth [21].

Path analysis revealed that nitrogen (N) uptake was strongly correlated with phosphorus (P) and potassium (K) uptake ($p \leq 0.01$). Potassium uptake exerted a significant direct effect on clipping yield (standardized estimate, SEs=0.57**, $p \leq 0.01$), whereas nitrogen and phosphorus uptake influenced clipping yield indirectly. Clipping yield had a strong direct effect on chlorophyll content (SEs=0.97**, $p \leq 0.01$) and an indirect effect on leaf color index (SEs=0.17^{NS}, $p>0.05$). TCI acted as a mediator linking clipping yield and chlorophyll content, with chlorophyll content being strongly influenced by leaf color index (SEs=0.83**, $p \leq 0.01$). Furthermore, clipping yield exerted both a direct effect on shoot length (SEs=0.48**, $p \leq 0.01$) and an indirect effect mediated through chlorophyll content (SEs=0.51**, $p \leq 0.01$). In contrast, root length showed neither significant direct effects (SEs=0.45^{NS}, $p>0.05$) nor indirect effects (SEs=0.51^{NS}, $p>0.05$) on clipping yield. The proposed path model demonstrated a satisfactory fit to the data. The chi-square test was not significant (χ^2=15.282, df=15, p=0.431), indicating good agreement between the observed and model-implied covariance matrices. The RMSEA value (0.035) suggested a close model fit, and the incremental fit indices exceeded the recommended thresholds (TLI=0.999, NFI=0.961, CFI=0.999, and RFI=0.927).

Synthesizing previous research and the path analysis results from this study, CFAA treatment promotes nitrogen uptake in turfgrass, increasing chlorophyll content and fresh biomass production, thereby improving turfgrass quality and growth. Additio-

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Agric. Environ. Sci. 2026, 45, 115-124

nally, nutrient absorption necessary for growth was also enhanced. These results suggest that application of amino acids could be effectively utilized to improve turf growth and quality, especially for cool-season grasses experiencing growth decline during high-temperature periods.

Conclusion

This study evaluated the effects of CFAA (compound fertilizer containing amino acids) application on soil chemical properties and the growth, quality, and nutrient dynamics of creeping bentgrass. The results demonstrated that CFAA application had minimal influence on soil chemical properties, as no significant changes were observed in soil pH, electrical conductivity, organic matter, total nitrogen, available phosphorus, or exchangeable potassium.

In contrast, CFAA application significantly enhanced turfgrass growth and quality, increasing the turf color index, chlorophyll a+b content (11.8–14.8%), shoot height (11.3–17.0%), and clipping yield (68.5–109.2%) compared with the control, with these parameters showing strong positive correlations with application rates. Additionally, both shoot and root growth were promoted, indicating improved overall plant growth.

Applying CFAA also markedly increased nitrogen, phosphorus, and potassium contents and their uptake in turfgrass tissues. Among these, nitrogen uptake played a central role in driving plant growth. Path analysis revealed that increased nitrogen uptake following CFAA application directly enhanced chlorophyll content and clipping yield, which subsequently improved turf color and shoot growth. Enhanced nitrogen uptake also promoted phosphorus and potassium absorption, contributing to overall plant development.

Overall, the findings indicate that CFAA application improves creeping bentgrass growth and quality primarily by promoting nitrogen uptake and associated physiological processes, rather than by altering soil chemical properties. Therefore, CFAA can be considered an effective management strategy for enhancing the growth and visual quality of cool-season turfgrass, particularly under conditions where growth is limited, such as during high-temperature periods.

Materials and Methods

Materials

This experiment was conducted over 12 months from June 2024 to March 2025 in the glass greenhouse of Daegu University's practice farm. The turfgrass used in the trial was creeping bentgrass (*A. stolonifera* L.; Penn-A1'), sown on June 5, 2024, and managed in pots for about six weeks. The soil in the experimental plots was composed of sand with a particle size distribution meeting the standards set by the United States Golf Association (USGA). Before the experiment, the soil chemical properties had a pH of 7.04 and an EC of 0.06 dS/m, indicating suitable conditions for turfgrass cultivation. For turf growth and nutrient supply, a compound fertilizer (N-P_2O_5-K_2O=10-5-30, C&L Chemical Co., Ltd., Seoul, Korea) and a compound fertilizer containing amino acids (CFAA; N-CaO=5.0-3.0, C&L Chemical Co., Ltd., Seoul, Korea) were used.

Establishing experimental treatments of CFAA

The treatment groups were established based on the manufacturer's recommended fertilization rate using a 500-fold diluted solution (CFAA 2 mL/m^2). The treatments were as follows: an no fertilizer group without fertilizer application (NF), a control group treated with compound fertilizer applied to the soil [control; N-P_2O_5-K_2O=10-5-30, 30 g/m^2, 3 N active ingredient (a.i.) N g/m^2], a treatment 1 group with CFAA diluted 1,000-fold (CFAA-1; control + CFAA 1 mL/m^2 per application), a treatment 2 group with CFAA diluted 500-fold (CFAA-2; control + CFAA 2 mL/m^2 per application), and a treatment 3 group with CFAA

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Agric. Environ. Sci. 2026, 45, 115-124

diluted 250-fold (CFAA-3; control + CFAA 4 mL/m^2 per application).

Experimental units consisted of 5-inch pots, and the experimental design was arranged in a completely randomized design with four replications. The compound fertilizer was applied at a rate corresponding to 3.0 g N a.i. g/m^2, starting from July 11, 2024, to February 20, 2025, at four-week intervals, for a total of nine applications. CFAA was diluted according to the treatment concentrations with tap water to prepare 1,000 mL per application and applied weekly from July 11, 2024, for a total of 37 applications (1,000 mL/m^2 diluted solution).

Investigation and analysis in creeping bentgrass applying CFAA

The growth of turfgrass was evaluated by measuring the TCI, chlorophyll a+b content, shoot height, clipping yield, nutrient content, and nutrient uptake. The TCI was assessed using a turf color meter (TCM 500, Spectrum Technologies, Inc., Plainfield, IL, USA) at weekly intervals, starting from July 18, for a total of 36 measurements, and monthly averages were calculated. Chlorophyll a+b content and clipping yield were measured every two weeks for a total of 18 times after fertilization.

Clippings were harvested at a height of 30 mm above the soil surface using sterilized scissors with 70% ethanol. The clipping yield for turf growth assessment was calculated by summing the clippings collected 14 and 28 days after fertilization. For chlorophyll a+b content measurement, a 0.1 g fresh sample from clippings collected on days 14 and 28 was extracted with 95% ethanol. The remaining clippings were dried at 70°C for 24 hours in a dryer (ON-11, Jeio Tech, Daejeon, Korea) to determine dry weight. Chlorophyll a+b content was analyzed using the method described by Kim [22], based on the extract obtained at −4°C with 95% ethanol.

Shoot height was measured from the soil surface to the tip of the leaf using a 150 mm ruler, recorded every 14 days from July 25, 2024, until the end of the experiment, for a total of 18 measurements. The average shoot height was calculated from the data obtained 14 and 28 days after fertilization.

Soil samples were collected twice, before the experiment (July 10, 2024) and after the experiment (March 20, 2025), to assess changes due to fertilizer application. After removing the turf from the pots, soil samples were collected for analysis. The samples were air-dried in the shade and passed through a 2 mm sieve before analysis. The analyzed soil properties included pH, EC, OM, T-N, Av.-P_2O_5, and Ex-K, following standard soil chemical analysis methods.

Statistical analysis

Statistical analyses were performed using SPSS (version 29, IBM, New York, USA). Differences between treatment means were evaluated by Duncan's multiple range test. Pearson correlation analysis was conducted to assess the relationships between CFAA application rates and measured variables. Additionally, changes in plants following CFAA treatment were analyzed through path analysis using SPSS AMOS (version 29, IBM, New York, USA).

Data Availability: All data are available in the main text or in the Supplementary Information. English translation and language polishing of the manuscript were assisted by the GPT AI model to ensure clarity and accuracy.

Author Contributions: Y.-S. Kim designed, performed the statistical analysis, wrote the first manuscript, and revised the manuscript, provide critical feedback; J.-H. Kang led the growth experiment, K.-M. Lee conceived the research, H.-Y. Choi collected the data, and J.-M. Cho performed the statistical pathway analysis with AMOS.

Notes: The authors declare no conflict of interest

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