

Effects of Elemental Sulfur and Seaweed Extract on Growth, Nutrient Status, and Physiological Quality of Bermuda Grass (*Cynodon dactylon*)

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Abstract

This study aimed to evaluate the individual and interactive effects of agricultural sulfur and seaweed extract on the vegetative growth, root development, and chemical and physiological characteristics of Bermuda grass (*Cynodon dactylon*) under hot arid conditions, concerning the combined application of agricultural sulfur and seaweed-based biostimulants for sustainable turfgrass management in arid and semi-arid environments. A field experiment was conducted at the experimental farm of the College of Agriculture, University of Diyala, Iraq, from July 2025 to January 2026 using a split-plot arrangement within a randomized complete block design (RCBD). Three sulfur levels 0.0, 1.5, and 2.0 t. ha⁻¹ and four seaweed extract concentrations (0, 5, 10, and 15 g experimental unit, corresponding to AE_1, AE2, AE3, and AE4) were evaluated with three replications. Agricultural sulfur levels were assigned to the main plots, while seaweed extract levels were allocated to the subplots. The evaluated parameters included plant height, shoot dry matter, root number, total chlorophyll content, and leaf concentrations of nitrogen, phosphorus, potassium, and soluble carbohydrates. The results revealed that agricultural sulfur, seaweed extract, and their interaction significantly (P 0.05) improved all measured growth, physiological, and chemical traits. The combined application of the highest sulfur level S3: 2.0 t. ha⁻¹ and the highest seaweed extract concentration AE4: 15 g experimental unit⁻¹) significantly increased responses, recording a plant height of 10.92 cm , shoot dry matter of 66.39% , root number of 27.00 roots plant⁻¹ , total chlorophyll content of 44.07 mg g⁻¹ FW , nitrogen content of 5.013% , phosphorus content of 0.5883% , potassium content of 4.613% , and soluble carbohydrates of 0.650%.

These findings demonstrate that integrating agricultural sulfur with seaweed extract represents an effective and sustainable management strategy for improving turfgrass growth, physiological performance, leaf nutrient concentrations {N} = 5.013%, {P} = 0.5883%, {K} = 4.613% , and overall quality under hot arid conditions while enhancing nutrient use efficiency and supporting environmentally sustainable landscape management.

Keywords: *Cynodon dactylon*; Agricultural sulfur; Seaweed extract; Biostimulants; Turfgrass; Hot arid conditions; Nutrient uptake;

Introduction

turfgrass represent an indispensable component of sustainable urban ecosystems because they improve environmental quality, , reduce surface temperatures, mitigate the urban heat island effect, and. Among urban landscape components, turfgrass systems provide additional ecological benefits by reducing soil erosion, improving rainwater infiltration, filtering airborne dust particles, and creating functional recreational areas. Consequently, maintaining high-quality turfgrass has become an essential objective of modern landscape management, particularly in regions characterized by hot and arid climates [1], [2].

Among warm season turfgrasses, Bermudagrass (*Cynodon dactylon* L.) belongs to the family Poaceae and is native to the tropical regions of Africa and Southeast Asia. It exhibits exceptional adaptability to warm climates, possessing high tolerance to drought, salinity, and diverse soil conditions in arid and semi-arid regions. is one of the most widely cultivated species because of its rapid establishment, aggressive stolon and rhizome development, excellent recuperative capacity, and high tolerance to mowing, traffic, and elevated temperatures. These characteristics make it the preferred turf species for sports fields, parks, golf courses, roadsides, and residential landscapes throughout tropical and subtropical regions. However, despite its adaptability, Bermudagrass frequently experiences reductions in shoot growth, root development, chlorophyll content, and overall turf quality when exposed to drought, salinity, prolonged heat stress, and alkaline soils with limited nutrient availability [1],

These environmental constraints not only impair the aesthetic and functional value of turfgrass but also increase irrigation demand and fertilizer inputs, thereby raising production costs and environmental risks. Consequently, considerable research has focused on developing sustainable management strategies that enhance plant growth and stress tolerance while reducing dependence on intensive chemical fertilization. Among the most promising approaches are the application of natural biostimulants, particularly seaweed extracts, together with soil amendments capable of improving nutrient availability under alkaline soil conditions [2].

Seaweed extracts have gained increasing attention because they contain numerous biologically active compounds, including phytohormones, amino acids, vitamins, polysaccharides, antioxidants, and mineral nutrients that collectively regulate plant metabolism and improve tolerance to environmental stress [3]. At the same time, elemental sulfur has become an important soil amendment for calcareous soils owing to its ability to reduce soil pH through microbial oxidation, thereby increasing the availability of essential nutrients and improving rhizosphere conditions for root growth [4]. The complementary roles of these two sustainable management practices provide a strong scientific basis for investigating their combined effects on Bermudagrass performance under hot arid environments.

Seaweed extracts have become one of the most widely studied natural biostimulants for sustainable turfgrass management because of their ability to enhance plant growth while reducing reliance on chemical

fertilizers. These extracts contain a diverse array of biologically active compounds, including phytohormones (auxins, cytokinins, and gibberellins), amino acids, polysaccharides, vitamins, antioxidants, betaines, and essential mineral nutrients, which collectively regulate plant metabolism and improve adaptation to environmental stresses [3], [6]. Unlike conventional fertilizers that primarily supply nutrients, seaweed extracts stimulate multiple physiological and biochemical processes, making them particularly valuable under drought, salinity, and high-temperature conditions.

Numerous studies have demonstrated that seaweed extracts improve Bermudagrass performance through several complementary mechanisms. Foliar applications stimulate root initiation and development, increase root biomass, enhance nutrient uptake, and improve water-use efficiency, enabling plants to maintain higher photosynthetic activity and better physiological performance under water-limited conditions [1], [5], [8]. Furthermore, repeated applications have been shown to preserve chlorophyll concentration, improve turf color and density, and maintain visual quality during periods of heat stress, largely through delaying leaf senescence and enhancing photosynthetic efficiency [2].

The beneficial effects of seaweed extracts are also associated with their capacity to strengthen plant defense systems against abiotic stress. Extracts derived from *Ascophyllum nodosum* have been reported to enhance drought and heat tolerance by improving osmotic adjustment, stabilizing cellular membranes, and activating antioxidant defense mechanisms that reduce oxidative damage caused by reactive oxygen species [3], [4]. In addition, the naturally

occurring phytohormones and signaling compounds present in brown algae regulate cell division, leaf expansion, tillering, and root elongation, thereby promoting vigorous vegetative growth and accelerating recovery following environmental or mechanical stress [6]. Collectively, these physiological responses improve nutrient-use efficiency, sustain plant metabolism, and enhance the persistence and overall quality of Bermudagrass under adverse environmental conditions [1].

Elemental sulfur is considered one of the most effective soil amendments for improving the productivity of turfgrass cultivated on calcareous and alkaline soils, where high soil pH restricts the availability of essential nutrients. Following microbial oxidation, elemental sulfur is converted into sulfuric acid, leading to a gradual reduction in soil pH and a consequent increase in the availability of phosphorus, iron, zinc, manganese, and other essential nutrients required for plant growth [8]. These improvements in soil chemical properties promote root development, enhance nutrient uptake, and improve the physiological performance and visual quality of Bermudagrass. In addition, sulfur application stimulates the activity of sulfur-oxidizing microorganisms, thereby improving rhizosphere processes and increasing nutrient cycling, which further enhances soil fertility and plant productivity [9].

Beyond its role in modifying soil chemistry, elemental sulfur contributes significantly to improving plant tolerance to environmental stresses. Sulfur-induced enhancement of nutrient availability promotes greater phosphorus solubility, improves mycorrhizal activity, and increases nutrient-use efficiency, resulting in more vigorous root

systems and greater biomass accumulation [10]. Furthermore, sulfur amendments have been associated with reduced incidence of soil-borne diseases, improved soil microbial diversity, and enhanced plant performance under saline conditions through better osmotic regulation and nutrient balance [11]. Long-term field studies have also demonstrated sustained improvements in turf density, ground cover, and overall quality following sulfur application, confirming its value as an environmentally sustainable management practice for Bermudagrass cultivated under alkaline soil conditions [12].

Although substantial progress has been made in understanding the individual effects of seaweed extracts, elemental sulfur, and foliar sulfur applications on turfgrass growth and stress tolerance, most previous studies have evaluated these management practices independently. Consequently, limited information is available regarding their integrated application, particularly in Bermudagrass (*Cynodon dactylon* L.) cultivated under the hot arid conditions and alkaline calcareous soils that prevail in many regions of the Middle East [13]. Since elemental sulfur primarily improves soil physicochemical and biological properties by increasing nutrient availability, whereas seaweed extracts enhance physiological processes, antioxidant defense, nutrient-use efficiency, and stress adaptation, their combined application may produce complementary or even synergistic responses that cannot be achieved by either treatment alone.

Furthermore, relatively few studies have simultaneously evaluated the effects of these treatments on vegetative growth, root development, chlorophyll content, and macronutrient accumulation (N, P, and K),

despite the close physiological relationships among these parameters and their collective influence on turf quality and persistence under stressful environments [14]. Addressing this knowledge gap is essential for developing environmentally sustainable management strategies capable of reducing fertilizer inputs while maintaining high-quality turfgrass under water-limited and alkaline soil conditions.

Therefore, the present study was conducted to evaluate the individual and combined effects of elemental sulfur and seaweed extract applications on the growth and physiological performance of Bermudagrass under hot, arid conditions. The study specifically examined their effects on vegetative growth, root development, chlorophyll content, and the uptake of nitrogen, phosphorus, and potassium. Furthermore, the research aimed to determine an efficient and environmentally sustainable management strategy for enhancing turfgrass quality and productivity under alkaline soil conditions

Materials and Methods

Experimental Site

A field experiment was conducted at the experimental farm of the College of Agriculture, University of Diyala, Iraq, located behind the college administration building, from 1 July 2025 to 1 January 2026 to investigate the individual and combined effects of agricultural sulfur and seaweed extract on the vegetative growth, physiological characteristics, and chemical composition of Bermudagrass (*Cynodon dactylon*).

The experimental field covered an area of 216 m² (24 × 9 m). Prior to planting, the soil

surface was prepared by adding two successive layers (10 cm each). The first layer consisted of silty agricultural soil, whereas the second layer consisted of river sediment collected from the Tigris River. The soil was thoroughly mixed, leveled, and prepared to provide a uniform seedbed. Composite soil samples were collected before treatment application for physical and chemical analyses, and the results are presented in

Vegetative sprigs of Bermudagrass were planted at 10-cm spacing to ensure rapid establishment and uniform turf coverage

throughout the experimental area in 1/7/2025

Experimental Factors: The experiment evaluated two factors: and seaweed extract.

Agricultural Sulfur (S) Agricultural sulfur (fine powder) was applied before planting by uniformly broadcasting the required quantity over the soil surface and incorporating it into the upper soil layer. Sulfur application was carried out under suitable weather conditions to minimize material loss and ensure uniform distribution. Three sulfur levels were evaluated:

Sulfur level	Treatment
0.0 t ha ⁻¹ (Control)	S1
1.5 t ha ⁻¹	S2
2.0 t ha ⁻¹	S3

Seaweed Extract (AE)

A commercial natural seaweed extract (Reef AlgaStar®, water-soluble flake) was used as the second experimental factor. According

to the manufacturer's specifications, the product contains:

Table (1) shows the contents of the Seaweed extract

Content	Component
45%	Organic matter
30%	<i>Ascophyllum nodosum</i> extract
1%	Total nitrogen (N)
1%	Available phosphorus (P ₂ O ₅)
20%	Soluble potassium (K ₂ O)
Present	Natural plant growth regulators
Present	Alginic acid
Present	Amino acids
Present	Vitamins

Content Component

Present Trace elements

The required amount of seaweed extract was dissolved in 20 L of water and applied as a foliar spray using a knapsack sprayer until

Seaweed extract level Treatment

0 g experimental unit⁻¹ (Control) AE1

5 g experimental unit⁻¹ AE2

10 g experimental unit⁻¹ AE3

15 g experimental unit⁻¹ AE4

The first foliar application was performed seven days after sulfur application, followed by four additional applications at regular intervals throughout the growing season. The chemical composition of the commercial seaweed extract is presented in

Experimental Design: The experiment was arranged as a split-plot experiment within a Randomized Complete Block Design (RCBD) with three replications. Agricultural sulfur levels were assigned to the main plots, whereas seaweed extract levels were allocated to the subplots. The experiment consisted of 12 treatment combinations (3 × 4) distributed randomly within each replication. Accordingly:

Each experimental unit measured 2 × 3 m (6 m²), whereas each replication occupied 72 m² (24 × 3 m).

Plastic barriers were installed between the main plots to prevent movement of irrigation water and applied materials. During foliar spraying, movable wooden shields were placed between adjacent experimental units to avoid spray drift.

Management of grass

All experimental units received identical cultural practices throughout the study.

complete leaf wetting. Four application levels were used:

Irrigation was applied uniformly according to crop water requirements to maintain adequate soil moisture. Weed control was carried out manually whenever necessary. Turfgrass mowing was performed using an electric mower whenever the canopy reached the recommended mowing height, while the cutting height was maintained at **4 cm** throughout the experiment to ensure uniform turf management among treatments. No additional management practices differed among treatments except for the experimental applications of agricultural sulfur and seaweed extract.

Growth, Physiological and Chemical Measurements

At the end of the experimental period, representative samples were collected randomly from each experimental unit to determine the vegetative growth, physiological, and chemical characteristics of Bermudagrass (*Cynodon dactylon*).

1-Plant Height: Plant height (cm plant⁻¹) was measured using a graduated ruler from the soil surface to the tip of the longest fully expanded leaf. Ten randomly selected plants from each experimental unit were measured, and the average value was recorded.

2-Shoot Dry Matter: Fresh shoots were harvested from each experimental unit, washed with distilled water, and oven-dried at 70°C to constant weight (approximately 72 h). Dry matter percentage was calculated according to the following equation:

$$\text{Dry Matter (\%)} = \frac{\text{Dry Weight}}{\text{Fresh Weight}} \times 100$$

3-Number of Roots: Ten plants were randomly excavated from each experimental unit. Soil particles were carefully removed by washing the roots with tap water followed by distilled water, and the total number of roots per plant was counted manually. The mean number of roots per plant was then calculated.

4-Total Chlorophyll Content: Fresh leaf samples were collected immediately after harvest. Total chlorophyll content was determined spectrophotometrically following acetone extraction (80% acetone) according to the method described by Arnon (1949). Absorbance was measured at 645 and 663 nm using a UV-Visible spectrophotometer, and total chlorophyll concentration was expressed as mg g^{-1} fresh weight (FW).

Chemical Analysis: Dried leaf samples were finely ground prior to chemical analysis.

5-Nitrogen (N) Total nitrogen concentration was determined using the micro-Kjeldahl digestion and distillation method as described by Results were expressed as percentage of dry weight.

6-Phosphorus (P) Phosphorus concentration was determined colorimetrically using the vanadomolybdate yellow color method after wet digestion according to. Absorbance was measured using a spectrophotometer, and phosphorus concentration was expressed as percentage of dry weight.

7-Potassium (K) Potassium concentration was determined using a Flame Photometer after wet digestion according to the method of and expressed as percentage of dry weight.

8-Carbohydrate content %: Total soluble carbohydrates were determined according to the phenol-sulfuric acid method described by Absorbance was measured spectrophotometrically at 490 nm, and carbohydrate concentration was expressed as percentage of dry weight.

Statistical Analysis: The experiment was arranged as a split-plot design within a randomized complete block design (RCBD) with three replications. Data was subjected to analysis of variance (ANOVA) using GenStat Statistical Software (22nd Edition, VSN International Ltd., Hemel Hempstead, UK). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% probability level ($P \leq 0.05$). All data presented in tables represent treatment means, and mean separation letters indicate statistically significant differences among treatments.

Results

Table -2 demonstrates that agricultural sulfur, seaweed extract, and their interaction significantly influenced the chemical composition of *Cynodon dactylon*. All evaluated parameters, including nitrogen, phosphorus, potassium, and total

carbohydrate contents, increased progressively with increasing sulfur application and seaweed extract concentration, indicating a synergistic effect between the two treatments on nutrient acquisition and metabolic activity.

Among sulfur treatments, the highest sulfur level (S3) consistently produced the greatest concentrations of all chemical constituents, recording mean values of 4.08% nitrogen, 0.5681% phosphorus, 4.3183% potassium, and 0.5892% soluble carbohydrates, whereas the lowest sulfur level (S1) resulted in the minimum values.

Seaweed extract also exerted a pronounced positive influence on all measured chemical characteristics. Plants treated with the highest extract concentration (AE4) exhibited the highest average nutrient contents, reaching 4.187% nitrogen, 0.5227% phosphorus, 3.803% potassium, and 0.5633% soluble carbohydrates, whereas untreated plants (AE1) recorded the lowest values. The beneficial effects of seaweed extracts are attributed to their rich composition of natural biostimulants, including auxins, cytokinins, betaines, amino acids, polysaccharides, vitamins, and micronutrients. These bioactive compounds stimulate root proliferation, increase root surface area, enhance membrane permeability, improve nutrient transport, and promote photosynthetic carbon fixation, collectively leading to greater nutrient accumulation within plant tissues.

The interaction between sulfur and seaweed extract was particularly evident. The combined treatment S3 $\times$ AE4 produced the highest values for all evaluated parameters, recording 5.013% nitrogen, 0.5883% phosphorus, 4.613% potassium, and 0.6500% soluble carbohydrates, while the control combination S1 $\times$ AE1 produced the lowest values (2.793%, 0.3913%, 2.073%, and 0.3433%, respectively). These results clearly demonstrate that sulfur fertilization and seaweed biostimulants acted synergistically rather than independently. Sulfur improved soil chemical conditions and nutrient availability, whereas seaweed extract enhanced root physiological activity and nutrient absorption efficiency. Consequently, plants receiving both treatments simultaneously exhibited superior nutritional status and carbohydrate synthesis compared with plants receiving either treatment alone.

Overall, these findings indicate that integrating agricultural sulfur with seaweed extract represents an effective management strategy for improving the nutritional quality and physiological performance of Bermuda grass under field conditions. The observed improvements in macronutrient accumulation and carbohydrate content are expected to support greater vegetative growth, enhanced turf quality, and increased tolerance to environmental stresses, making this integrated approach particularly suitable for sustainable turfgrass management in arid and semi-arid regions.

Table 2. Effect of Agricultural Sulfur (S), Seaweed Extract (AE), and Their Interaction on the Chemical Characteristics of Bermuda Grass (*Cynodon dactylon*)

Soluble carbohydrates (%)	Potassium (%)	Phosphorus (%)	Nitrogen (%)	Seaweed extract levels	Sulfur levels
0.34333 h	2.073 L	0.3913 L	2.793 L	AE1	S1
0.45667 gf	2.393 K	0.4043 K	2.983 K	AE2	
0.47000 f	2.713 J	0.4283 J	3.193 J	AE3	
0.50000 e	2.963 I	0.4533 I	3.333 I	AE4	
0.4425 c	2.5358 C	0.4193 C	3.076 C	Mean S1	S2
0.43000 g	3.163 H	0.4833 H	3.513 H	AE1	
0.46000 f	3.393 G	0.5023 G	3.813 G	AE2	
0.51000 e	3.623 F	0.5143 F	4.083 F	AE3	
0.54000 d	3.833 E	0.5263 E	4.213 E	AE4	S3
0.4850 B	3.5033 B	0.5066 B	3.9058 B	Mean S2	
0.52333	4.043 D	0.5433 D	4.363 D	AE1	
0.57000 c	4.253 C	0.5643 C	4.543 C	AE2	
0.61333 b	4.363 B	0.5763 B	4.773 B	AE3	Mean of seaweed extract
0.65000 a	4.613 A	0.5883 A	5.013 A	AE4	
0.5892 A	4.3183 A	0.5681 A	4.6733 A	Mean S3	
0.4322 D	3.093 D	0.4727 D	3.557 D	AE1	
0.4956 C	3.347 C	0.4903 C	3.780 C	AE2	
0.5311 B	3.567 B	0.5063 B	4.017 B	AE3	
0.5633 A	3.803 A	0.5227 A	4.187 A	AE4	

Means followed by different letters within each column differ significantly according to **Duncan's Multiple Range Test at $P \leq 0.05$** .

The results presented in Table 3 indicate that agricultural sulfur, seaweed extract, and their interaction significantly ($P \leq 0.05$) affected the vegetative and root growth of Bermuda grass (*Cynodon dactylon*). Significant improvements were observed in plant height, shoot dry matter, root number, and total chlorophyll content as sulfur level and seaweed extract concentration increased, demonstrating the complementary

roles of soil amendment and biostimulant application in promoting turfgrass growth.

Increasing sulfur application markedly enhanced vegetative performance. The highest sulfur level (S3) produced the greatest shoot dry matter (58.65%) and total chlorophyll (40.73 mg g⁻¹ FW), while plant height reached 7.31 cm compared with 5.55 cm under S1. Likewise, sulfur significantly increased root development, with S2 and S3

producing substantially more roots than S1. These improvements can be attributed to sulfur's role in soil acidification following microbial oxidation, which increases the availability of phosphorus and several micronutrients while enhancing nitrogen utilization. Sulfur is also an essential constituent of the amino acids cysteine and methionine and numerous enzymes involved in protein synthesis, chlorophyll formation, and photosynthetic metabolism. Consequently, improved sulfur nutrition stimulates cell division, leaf expansion, and biomass accumulation.[15]

Seaweed extract significantly enhanced all measured growth parameters. The highest application level (AE4) resulted in the greatest plant height (8.89 cm), shoot dry matter (55.32%), root number (25.44 roots plant⁻¹), and total chlorophyll (41.07 mg g⁻¹ FW). These responses reflect the well-

established biostimulant properties of seaweed extracts, which supply naturally occurring phytohormones such as auxins and cytokinins together with amino acids, vitamins, osmoprotectants, polysaccharides, and mineral nutrients. These compounds stimulate root initiation and elongation, enhance nutrient uptake efficiency, delay chlorophyll degradation, and increase photosynthetic capacity, thereby improving overall plant vigor.

The interaction between sulfur and seaweed extract produced even greater improvements than either treatment alone. The combined treatment S3 × AE4 recorded the maximum values for plant height (10.92 cm), shoot dry matter (66.39%), root number (27.00 roots plant⁻¹), and total chlorophyll (44.07 mg g⁻¹ FW). In contrast, the control treatment (S1 × AE1) produced the lowest values for all measured traits.

Table 3. Effect of Agricultural Sulfur (S), Seaweed Extract (AE), and Their Interaction on Vegetative and Root Growth Characteristics of Bermuda Grass (*Cynodon dactylon*)

Total chlorophyll (mg g ⁻¹ FW)	Number of roots (roots plant ⁻¹)	Shoot dry matter (%)	Plant height (cm plant ⁻¹)	Seaweed extract levels	Sulfur levels
34.277 g	9.667 f	35.894 h	3.1667 f	AE1	S1
36.753 feg	15.667 d	39.127 g	5.600 de	AE2	
35.517 g	19.667 c	42.985 f	6.1667 dc	AE3	
37.180 fedg	22.000 cb	45.345 e	7.2500 c	AE4	
35.9317 B	16.7500 B	40.8377 C	5.5458 B	Mean S1	
39.840 bedc	12.667 e	47.308 e	4.5500 e	AE1	S2
40.217 bdc	22.000 cb	50.899 d	6.800 dc	AE2	
39.240 bedc	22.667 b	51.724 dc	7.1100 c	AE3	
41.960 ba	27.333 a	54.226 c	8.4900 b	AE4	
40.3142 A	21.1667 A	51.0393 B	6.7375 A	Mean S2	
39.367 bedc	12.000 fe	54.340 c	6.7100 dc	AE1	S3
38.270 fedc	21.667 cb	54.768 c	6.0000 dc	AE2	
41.220 bac	22.667 b	59.118 b	5.6000 de	AE3	
44.070 a	27.000 a	66.386 a	10.9200 a	AE4	

Total chlorophyll (mg g ⁻¹ FW)	Number of roots (roots plant ⁻¹)	Shoot dry matter (%)	Plant height (cm plant ⁻¹)	Seaweed extract levels	Sulfur levels
40.7317 A	20.8333 A	58.6529 A	7.3075 A	Mean S3	
37.8278 B	11.4444 D	45.8472 D	4.8089 C	AE1	Mean of seaweed extract
38.4133 B	19.7778 C	48.2644 C	6.1333 B	AE2	
38.6589 B	21.6667 B	51.2759 B	6.2922 B	AE3	
41.0700 A	25.4444 A	55.3190 A	8.8867 A	AE4	

Means followed by different letters within each column differ significantly according to Duncan's Multiple Range Test at $P \leq 0.05$.

Discussion

The present study demonstrated that the integrated application of agricultural sulfur and seaweed extract substantially enhanced the vegetative growth, root development, physiological performance, and chemical composition of Bermuda grass (*Cynodon dactylon*) under hot arid field conditions. Improvements were consistently observed across all measured parameters, including plant height, shoot dry matter, root number, total chlorophyll, nitrogen, phosphorus, potassium, and soluble carbohydrates, indicating that the combined treatment positively influenced both plant growth and metabolism. These findings support the hypothesis that integrating soil amendments with plant biostimulants produces greater benefits than applying either input individually.[16]

The positive response to sulfur application can be explained by its central role in improving soil fertility and nutrient dynamics. Following microbial oxidation, elemental sulfur lowers rhizosphere pH, thereby increasing the availability of phosphorus and several essential nutrients

while improving nutrient uptake efficiency. Sulfur is also indispensable for the synthesis of sulfur-containing amino acids, proteins, coenzymes, and chlorophyll, all of which contribute directly to photosynthetic efficiency, carbon assimilation, and biomass production. Consequently, plants supplied with higher sulfur levels exhibited superior vegetative growth and improved nutritional status.

Seaweed extract further enhanced plant performance through a different but complementary mechanism. The extract provides a complex mixture of naturally occurring bioactive compounds, including auxins, cytokinins, amino acids, betaines, polysaccharides, vitamins, and micronutrients, which stimulate root development, enhance nutrient absorption, maintain chlorophyll stability, and improve physiological activity. These compounds increase the plant's metabolic capacity and enable more efficient utilization of available nutrients, resulting in greater biomass accumulation and improved chemical composition.

A particularly important outcome of this study is the clear synergistic interaction observed between agricultural sulfur and seaweed extract, as the highest treatment combination consistently yielded superior performance across all vegetative, physiological, and chemical parameters compared to individual applications. This synergistic response suggests that sulfur primarily optimized the root-zone environment by lowering soil pH and enhancing macro- and micronutrient availability, whereas seaweed extract simultaneously expanded the plant's physiological capacity to absorb, transport, and metabolize those available nutrients through biostimulatory pathways. Furthermore, the strong physiological interconnections among elevated chlorophyll concentration, macronutrient accumulation (N , P , K), soluble carbohydrate content, and biomass production highlight a well-coordinated metabolic response. Specifically, improved nitrogen uptake facilitated chlorophyll biosynthesis and photosynthetic carbon assimilation, phosphorus supplied essential chemical energy (ATP) for metabolic pathways, and potassium regulated osmotic balance, stomatal conductance, and assimilate translocation. Integrated together, these complementary soil-plant mechanisms enhanced net photosynthetic efficiency and assimilate accumulation, ultimately explaining the robust vegetative establishment, biomass production, and stress tolerance observed under the combined sulfur and seaweed treatments [16].

From an agronomic perspective, the results highlight the potential of combining agricultural sulfur with seaweed biostimulants as a sustainable nutrient management strategy for turfgrass

production in arid and semi-arid regions. This integrated approach not only improves plant growth and nutritional quality but may also reduce dependence on intensive chemical fertilization by increasing nutrient use efficiency and enhancing plant resilience under environmental stress. These findings indicate a clear synergistic relationship between sulfur nutrition and seaweed biostimulants, where agricultural sulfur improves soil chemical properties and nutrient availability, while seaweed extract enhances root proliferation and physiological activity, enabling Bermudagrass to utilize the increased nutrient supply more efficiently. Notably, the observed enhancement in root growth closely paralleled the increases in chlorophyll concentration and shoot dry matter accumulation, as a more developed root system expands the absorptive surface area for water and nutrient uptake, while higher photosynthetic pigment levels improve light-harvesting efficiency and carbon assimilation. Overall, the integrated application of agricultural sulfur and seaweed extract proved to be an effective strategy for promoting biomass production, chlorophyll synthesis, and root development, ultimately enhancing turf establishment, canopy density, and physiological resilience under the stressful conditions of arid and semi-arid environments where nutrient availability and water-use efficiency are critical determinants of turf quality [15].

Importantly, this study addresses an existing knowledge gap regarding the integrated application of elemental sulfur and seaweed extract in Bermudagrass (*Cynodon dactylon*), as previous investigations have primarily focused on their individual impacts rather than their joint application under hot arid conditions. The present findings demonstrate that elemental sulfur

nutrition significantly enhances soil nutrient availability and uptake, as soil microbial oxidation converts elemental sulfur into sulfuric acid (H_2SO_4), thereby reducing rhizosphere pH and increasing the solubility and mobility of fixed phosphorus and essential micronutrients. Beyond modifying soil chemical properties, sulfur serves as an indispensable constituent of sulfur-containing amino acids (methionine and cysteine), functional proteins, and metabolic coenzymes that directly regulate nitrogen assimilation and photosynthetic carbon pathways. Consequently, optimized sulfur nutrition promotes chlorophyll biosynthesis, activates key metabolic enzymes, and enhances carbohydrate accumulation, establishing a practical framework for sustainable turfgrass management and quality enhancement under water-limited environments[16].

Conclusion

The integrated application of agricultural sulfur and seaweed extract significantly improved the growth, physiological characteristics, and chemical composition of Bermuda grass under hot arid conditions. The combined treatment consistently outperformed the individual applications, confirming a synergistic interaction between sulfur-induced improvements in soil nutrient availability and seaweed-mediated stimulation of plant physiological processes. Enhanced nutrient uptake, chlorophyll synthesis, carbohydrate accumulation, and root development collectively contributed to greater biomass production and overall turf quality.

These findings demonstrate that integrating agricultural sulfur with seaweed extract represents an effective and sustainable

management strategy for improving Bermuda grass performance in arid and semi-arid environments. The study also provides new evidence supporting the combined use of soil amendments and biostimulants to enhance nutrient use efficiency and turf resilience, thereby contributing to more sustainable landscape management practices under challenging climatic conditions.

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