

Evaluation of the Chemical Content of Water-Stressed Goldenrod Plant Under the Influence of Tissue Polyter and Nano-Chitosan

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Abstract An independent factorial experiment was conducted in one of the plastic greenhouses designated for this purpose in Karbala, Al-Husseiniya district, located 14 km from the city center, during the 2024–2025 agricultural season. The aim was to study the effect of natural compounds on the chemical content of goldenrod plants subjected to water stress under greenhouse conditions. The experiment involved three factors: the first factor was water stress, i.e., irrigation at three intervals (every 4, 6, and 8 days); the second factor was the use of tissue politer at three levels (0, 2.50, and 5 g pot⁻¹), applied once at seedling transplanting; and the third factor was foliar spraying with nano-chitosan at three levels (0, 100, and 200 mg L⁻¹), applied four times during the experiment. The experiment was arranged in a randomized complete block design with three replications, and results were analyzed at a 5% probability level. The combined factors showed significant effects on the percentages of nitrogen, phosphorus, and potassium. The highest values were obtained under the treatment combination of irrigation every 4 days, soil application of tissue politer at 5 g, and foliar spraying with nano-chitosan at 200 mg L⁻¹, reaching (3.937, 1.197, and 2.263)% respectively. In contrast, the lowest values were recorded under irrigation every 8 days, with soil free of politer and spraying with distilled water only, reaching (3.003, 1.030, and 1.297)% respectively.

Keywords: Tissue politer; Nano-chitosan; Water stress

1. INTRODUCTION

Goldenrod (*Solidago canadensis* L.), belonging to the family Asteraceae, is renowned for its bright yellow flowers that bloom in late summer and early autumn. Originally native to North America, this plant is now cultivated in many regions worldwide for ornamental and medicinal purposes. Owing to its beauty and benefits, goldenrod has become a symbol of purity and strength in certain cultures. Today, it is widely used in modern herbal medicine as well as in natural garden design, adding vibrant colors and vitality to landscapes [1].

Tall stems that may exceed two meters in height and small flowers clustered in dense panicles resembling spikes characterize goldenrod. It is considered an important plant for attracting bees and butterflies, thereby supporting biodiversity. From a medical perspective, goldenrod has been used since ancient times in folk medicine to treat urinary tract infections, kidney stones, joint pain, and colds. These therapeutic properties are attributed to its active compounds, including flavonoids and saponins, which possess anti-inflammatory and

antioxidant effects [2]. In light of accelerating climate change and increasing human pressures, Iraq is facing an escalating crisis of water scarcity. This acute shortage of water resources is attributed to several factors, including reduced rainfall, rising temperatures, depletion of groundwater, and others. At the same time, consumption and discharge have increased, with agriculture being one of the largest consumers of water in Iraq, accounting for more than 85% of water use in some regions. This has had a negative impact on green cover, and as a result of limited water resources, cultivated areas have shrunk, leading to reduced crop production and deterioration of soil quality (such as increased salinity and drought) due to reduced irrigation. Consequently, the ability of plants to absorb nutrients is negatively affected [3]. Given these challenges, it is essential to adopt strategies and methods to mitigate the negative impact of water scarcity on soils and green areas. Recent studies have proposed the use of natural chemical compounds with biostimulant properties to overcome water shortages. Such compounds can reduce water loss from soil and enhance moisture retention to cope with drought. One example is tissue politer, a natural polymer derived from plant cellulose fibers that bind with soil particles, thereby reducing water permeability and retaining moisture for longer periods [4].

Plant resilience can also be enhanced by reducing water loss through transpiration using antitranspirants. These compounds are effective in limiting water vapor loss from plants by strengthening cell walls when applied as foliar sprays. Chitosan, for instance, enhances plant resistance to abiotic stresses such as water deficit, high salinity, and toxic metals [5]. Moreover, chitosan nanoparticles act as a protective barrier against environmental stressors such as moisture deficiency, helping stabilize nutrients and facilitating their uptake by plants over extended periods [6].

2. MATERIALS AND METHODS

A factorial experiment was conducted in one of the plastic greenhouses designated for this purpose in Al-Husseiniya district (14 km southeast of Karbala Governorate), located at longitude 44°09'40.9" E and latitude 32°39'44.0" N. The experiment was carried out on vegetative-origin goldenrod plants, which were transplanted into plastic pots with a diameter of 30 cm and a soil capacity of 8 kg. The soil mixture consisted of sandy soil and peat moss at a ratio of 2:3 (Table 1). Each pot contained one plant, and all necessary cultural practices were applied throughout the experimental period whenever required.

Table (1): Some chemical and physical properties of the experimental soil.

Soil Texture		Soil particle size distribution			Available Potassium (mg. kg ⁻¹)	Available Phosphorus (mg. kg ⁻¹)	Total Nitrogen (mg. kg ⁻¹)	Organic Matter (%)	E.C ms. cm ⁻¹	pH
Sand (%)	(%) Silt	Clay (%)								
Sandy										
89.50	8.46	2.03		106.96	0.3	9.1	0.33	18.96	7.58	

2.1 Experimental Factors

- **Irrigation intervals:** Applied at three levels (every 4, 6, and 8 days, respectively). The irrigation program prepared in the study was initiated after the implementation of the experimental treatments.
- **Tissue Polyter:** Obtained from the Tissue Culture Palms Center, Kuwait. The soil of the pots was treated with three levels of tissue polyter (0, 2.5, and 5 g pot⁻¹). The material was applied only once at the time of transplanting goldenrod seedlings on October 25. The recommended amount of polyter was placed beneath the root zone soil, followed by watering and completion of the transplanting process.
- **Nanochitosan:** With the chemical formula C₅₆H₁₀₃N₉O₃₉ and purity of 99.5%, produced by EPRUI Nanomaterials Company. It was applied as a foliar spray at four intervals, each separated by 20 days, starting from March 29 until June 1. Spraying was carried out early in the morning until complete wetting of the foliage, using three concentrations (0, 100, and 200 mg L⁻¹).

2.2 Studied Traits

Measurements were conducted at Al-Fouad Scientific Laboratories in Baghdad at the end of the experimental period and included the following:

1. **Leaf content of macronutrients (%):**
 - Plant leaf samples (0.2 g dry weight) were digested using sulfuric and perchloric acids at a ratio of 4:1. After digestion, the following elements were determined:
 - **Nitrogen (%):** Measured as total nitrogen percentage using Micro Kjeldahl apparatus after adding sodium hydroxide (10 M) and titrating with hydrochloric acid (0.04 N).
 - **Phosphorus (%):** Determined according to the method described by Olsen and Sommer [7].
 - **Potassium (%):** Determined according to the method described by Hesse [8]. using a flame photometer.
2. **Leaf carbohydrate content (%):**
 - Estimated according to the method of Joslyn [9]. The total carbohydrate content was calculated using the following equation: [equation provided in original method].
3. **Leaf protein percentage (%):**
 - Calculated according to the method of Crasser and Parsons [10], based on the measured total nitrogen percentage, using the formula:
Protein % = N % x 6.25

3. RESULTS

3.1 Estimation of leaf nitrogen content

The experimental factors showed significant effects on the studied traits. Water stress had a clear impact on nitrogen percentage: irrigation every 4 days gave the highest nitrogen content (3.560%), surpassing all other treatments, while irrigation every 8 days resulted in the lowest

value (3.293%). Regarding the polyter factor, the treatment with 5 g polyter recorded the highest nitrogen percentage (3.648%), whereas the control treatment gave the lowest value (3.130%). For the nano-chitosan foliar spray factor, a significant effect was observed. Spraying at the level of 200 mg·L⁻¹ produced the highest nitrogen content (3.507%), which was not significantly different from spraying at 100 mg·L⁻¹. In contrast, the control treatment plants had 3.396% nitrogen. The two-way interactions also revealed significant effects: The interaction of irrigation every 4 days with 5 g polyter per pot gave the highest nitrogen percentage (3.821%), outperforming all other treatments. The lowest value (3.027%) was obtained from the interaction of irrigation every 8 days without polyter addition. The interaction between irrigation intervals and nano-chitosan spraying showed that irrigation every 4 days combined with spraying at 200 mg·L⁻¹ resulted in the highest nitrogen content (3.669%), while irrigation every 8 days with water spray only gave the lowest value (3.264%). The interaction between polyter and nano-chitosan also had a significant effect: spraying with nano-chitosan at 200 mg·L⁻¹ combined with 5 g polyter produced the highest nitrogen percentage (3.728%), whereas the control treatment recorded the lowest value (3.082%). The triple interaction of the experimental factors was clearly significant. The treatment combining irrigation every 4 days + 5 g polyter + foliar spray with nano-chitosan at 200 mg·L⁻¹ produced the highest nitrogen percentage (3.937%), while the lowest value (3.003%) was obtained from the treatment combining irrigation every 8 days + no polyter addition + nano-chitosan spray at 100 mg·L⁻¹.

Table 2. The effect of polyter, nano-chitosan, and their interactions on leaf nitrogen content (%) of Solidago plants grown under different irrigation intervals.

Irrigation period (day)	Polyter (gmPot ⁻¹)	Nanochitosan (mg.l ⁻¹)			Irrigation period X polyter
		0.00	100	200	
4	0.00	3.110	3.363	3.450	3.308
	2.50	3.613	3.423	3.620	3.552
	5.00	3.710	3.817	3.937	3.821
6	0.00	3.100	3.007	3.057	3.055
	2.50	3.623	3.780	3.757	3.720
	5.00	3.613	3.703	3.763	3.693
8	0.00	3.037	3.003	3.040	3.027
	2.50	3.383	3.433	3.453	3.423
	5.00	3.373	3.430	3.483	3.429
L.S.D. 0.05		0.3345			0.1931
Irrigation period X nanochitosan					Irrigation period
4		3.478	3.534	3.669	3.560
6		3.445	3.497	3.526	3.489
8		3.264	3.289	3.325	3.293
L.S.D. 0.05		0.1931			0.1115
Nanochitosan X Polyter					Polyter
0.00		3.082	3.124	3.182	3.130
2.50		3.540	3.545	3.610	3.565
5.00		3.565	3.650	3.728	3.648
L.S.D. 0.05		0.1931			0.1115
Nanochitosan		3.396	3.440	3.507	
L.S.D. 0.05		0.1115			

3.2 Estimation of leaf phosphorus content

Table (3) shows the results of the experimental factors on phosphorus content in plant leaves. Irrigation intervals had a significant effect: irrigation every 4 days gave the highest phosphorus percentage (1.125%), while irrigation every 8 days resulted in the lowest value (1.091%). The polyter factor also showed significant superiority: the treatment with 5 g polyter recorded the highest phosphorus percentage (1.120%), which was not significantly different from the 2.50 g treatment. The lowest phosphorus content was observed in the control treatment (1.094%). For the nano-chitosan factor, spraying at 200 mg·L⁻¹ significantly outperformed the other treatments, giving the highest phosphorus percentage (1.139%), while the control treatment recorded the lowest value (1.059%).

Regarding the two-way interaction between irrigation intervals and polyter, the treatment combining irrigation every 4 days + 5 g polyter produced the highest phosphorus percentage (1.138%), while the lowest value (1.079%) was obtained from the treatment combining irrigation every 8 days + no polyter addition.

Table 3. Effect of polyter, nano-chitosan, and their interactions on leaf phosphorus content (%) of Solidago plants grown under different irrigation intervals.

Irrigation period (day)	Polyter (gmPot ⁻¹)	Nanochitosan (mg.l ⁻¹)			Irrigation period X polyter
		0.00	100	200	
4	0.00	1.057	1.133	1.137	1.109
	2.50	1.070	1.140	1.173	1.128
	5.00	1.087	1.130	1.197	1.138
6	0.00	1.047	1.120	1.110	1.092
	2.50	1.070	1.087	1.140	1.099
	5.00	1.077	1.133	1.143	1.118
8	0.00	1.030	1.107	1.100	1.079
	2.50	1.033	1.113	1.120	1.089
	5.00	1.063	1.123	1.127	1.104
L.S.D. _{0.05}			0.07		0.04
Nanochitosan X Irrigation period					Irrigation
	4	1.071	1.134	1.169	1.125
	6	1.065	1.113	1.131	1.103
	8	1.042	1.114	1.116	1.091
L.S.D. _{0.05}			0.04		0.023
Polyter X nanochitosan					Polyter
	0.00	1.045	1.120	1.116	1.094
	2.50	1.058	1.113	1.144	1.105
	5.00	1.076	1.129	1.156	1.120
L.S.D. _{0.05}			0.04		0.023
Nanochitosan		1.059	1.121	1.139	
L.S.D. _{0.05}			0.023		

The two-way interaction between irrigation intervals and nano-chitosan showed that the highest phosphorus percentage (1.169%) was obtained from the treatment combining irrigation every 4 days + nano-chitosan spray at 200 mg·L⁻¹, while the lowest value (1.042%) resulted from the treatment combining irrigation every 8 days + distilled water spray. For the two-way interaction between polyter and nano-chitosan, the treatment combining 5 g polyter + nano-chitosan spray at 200 mg·L⁻¹ produced the highest phosphorus percentage (1.156%), whereas the lowest value (1.045%) was recorded in the control treatment. Three-way

interaction for phosphorus content. The highest phosphorus percentage (1.197%) was obtained from the triple interaction combining irrigation every 4 days + nano-chitosan spray at 200 mg·L⁻¹ + 5 g polyter, while the lowest value (1.030%) was recorded from the treatment combining irrigation every 8 days + no polyter addition + distilled water spray only.

3.3 Estimation of leaf potassium content

The statistical analysis (Table 4) revealed significant effects of the experimental factors on potassium content. Irrigation intervals had a clear influence: irrigation every 4 days produced the highest potassium percentage (2.079%), while irrigation every 8 days gave the lowest value (1.528%). For the polyter factor, no significant differences were observed among the tested levels. In contrast, the nano-chitosan factor showed significant differences: spraying at 200 mg·L⁻¹ resulted in the highest potassium percentage (1.920%), which was not significantly different from spraying at 100 mg·L⁻¹. The lowest value (1.584%) was recorded in the control treatment. Two-way interactions for potassium content. The interaction between irrigation intervals and polyter showed significant differences: the treatment combining irrigation every 4 days + 5 g polyter produced the highest potassium percentage (2.148%), while the lowest value (1.441%) was obtained from the treatment combining irrigation every 8 days + 2.5 g polyter. The interaction between irrigation intervals and nano-chitosan revealed that irrigation every 4 days + nano-chitosan spray at 200 mg·L⁻¹ gave the highest potassium percentage (2.182%), which was not significantly different from the treatment combining irrigation every 4 days + nano-chitosan spray at 100 mg·L⁻¹. The lowest value (1.346%) was recorded from the treatment combining irrigation every 8 days + no nano-chitosan spray.

Table 4. Effect of polyter, nano-chitosan, and their interactions on leaf potassium content (%) of *Solidago* plants grown under different irrigation intervals.

Irrigation period	Polyter (gm.Pot ⁻¹)	Nanochitosan (mg.L ⁻¹)			Irrigation period X
		0.00	100	200	
4	0.00	1.710	2.090	2.040	1.947
	2.50	2.053	2.130	2.243	2.142
	5.00	2.000	2.180	2.263	2.148
6	0.00	1.600	1.817	1.807	1.741
	2.50	1.467	2.093	1.880	1.813
	5.00	1.387	1.533	1.867	1.596
8	0.00	1.303	1.643	1.820	1.589
	2.50	1.297	1.363	1.663	1.441
	5.00	1.437	1.527	1.700	1.554
L.S.D. 0.05		0.5377			0.3104
Irrigation period X nanochitosan					Irrigation
4		1.921	2.133	2.182	2.079
6		1.484	1.814	1.851	1.717
8		1.346	1.511	1.728	1.528
L.S.D. 0.05		0.3104			0.1792
Polyter X nanochitosan					Polyter
	0.00	1.538	1.850	1.889	1.759
	2.50	1.606	1.862	1.929	1.799
	5.00	1.608	1.747	1.943	1.766
L.S.D. 0.05		0.3104			N.S
Nanochitosan		1.584	1.820	1.920	
L.S.D. 0.05		0.1792			

From the same table, the two-way interaction between polyter and nano-chitosan showed significant differences. The treatment combining 5 g polyter + nano-chitosan spray at 200

mg·L⁻¹ produced the highest potassium percentage (1.943%), while the lowest value (1.538%) was recorded in the control treatment.

Three-way interaction for potassium content. The highest potassium percentage (2.263%) was obtained from the triple interaction combining irrigation every 4 days + nano-chitosan spray at 200 mg·L⁻¹ + 5 g polyter, whereas the lowest value (1.297%) was recorded from the treatment combining irrigation every 8 days + 2.5 g polyter + no nano-chitosan spray.

3.4 Estimation of leaf protein percentage

Table (5) shows significant differences among treatments. The irrigation interval factor had a clear effect: irrigation every 4 days resulted in the highest protein percentage (27.22%), while irrigation every 8 days gave the lowest value (23.86%). For the polyter factor, no significant differences were observed among its levels. In contrast, the nano-chitosan factor showed significant superiority: spraying at 200 mg·L⁻¹ produced the highest protein percentage (26.83%), while the control treatment recorded the lowest value (24.39%). Two-way interactions for protein content The interaction between irrigation intervals and polyter showed significant differences: the treatment combining irrigation every 4 days + 2.5 g polyter per pot gave the highest protein percentage (28.00%), while the lowest value (23.17%) was obtained from the treatment combining irrigation every 8 days + 2.5 g polyter per pot. The interaction between irrigation intervals and nano-chitosan also showed significant effects: the treatment combining irrigation every 4 days + nano-chitosan spray at 200 mg·L⁻¹ produced the highest protein percentage (29.66%), while the lowest value (23.19%) was recorded from the treatment combining irrigation every 8 days + no nano-chitosan spray.

Table 5. Effect of polyter, nano-chitosan, and their interactions on leaf protein content (%) of Solidago plants grown under different irrigation intervals.

Irrigation period (day)	Polyter (gmPot ⁻¹)	Nanochitosan (mg.l ⁻¹)			Irrigation period X polyter
		0.00	100	200	
4	0.00	23.64	25.74	28.35	25.91
	2.50	24.66	28.16	31.16	28.00
	5.00	25.80	27.95	29.46	27.74
6	0.00	26.08	24.91	29.20	26.73
	2.50	25.39	25.39	26.39	25.73
	5.00	24.32	23.89	26.02	24.75
8	0.00	21.94	24.59	25.18	23.90
	2.50	23.58	24.80	21.12	23.17
	5.00	24.06	24.82	24.61	24.50
L.S.D. _{0.05}			2.744		1.584
Nanochitosan X Irrigation period					Irrigation
	4	24.70	27.28	29.66	27.22
	6	25.27	24.73	27.20	25.73
	8	23.19	24.74	23.64	23.86
L.S.D. _{0.05}			1.584		0.915
Polyter X Nanochitosan					Polyter
	0.00	23.89	25.08	27.58	25.51
	2.50	24.55	26.12	26.22	25.63
	5.00	24.73	25.55	26.70	25.66
L.S.D. _{0.05}			1.584		N.S
Nanochitosan		24.39	25.58	26.83	
L.S.D. _{0.05}			0.915		

The two-way interaction between polyter and nano-chitosan showed significant differences. The treatment combining nano-chitosan spray at 200 mg·L⁻¹ without polyter

addition produced the highest protein percentage (27.58%), while the lowest value (23.89%) was recorded in the control treatment. Significant differences were also observed in the triple interaction. The treatment combining irrigation every 4 days + 2.5 g polyter + nano-chitosan spray at 200 mg·L⁻¹ produced the highest protein percentage (31.16%). In contrast, the lowest value (21.12%) was obtained from the treatment combining irrigation every 8 days + 2.5 g polyter per pot + nano-chitosan spray at 200 mg·L⁻¹.

3.5 Estimation of carbohydrate content

Table (6) shows significant differences in carbohydrate content. The irrigation interval factor had a clear effect: irrigation every 4 days resulted in the highest carbohydrate percentage (45.69%), while irrigation every 8 days gave the lowest value (44.58%). For the polyter factor, no significant differences were observed among its levels. In contrast, the nano-chitosan factor showed significant superiority: spraying at 200 mg·L⁻¹ produced the highest carbohydrate percentage (46.08%), while the control treatment recorded the lowest value (43.38%). The interaction between irrigation intervals and polyter showed significant differences: the treatments combining irrigation every 4 days + polyter at 2.5 g and 5 g per pot produced the highest carbohydrate percentage (45.82%), while the lowest value (44.29%) was obtained from the treatment combining irrigation every 8 days + no polyter addition.

Table (6): Effect of polyter, nano-chitosan, and their interactions on leaf carbohydrate content (%) of Solidago plants grown under different irrigation intervals.

Irrigation period (day)	Polyter (gmPot ⁻¹)	Nanochitosan (mg.l ⁻¹)			Irrigation period X polyter
		0.00	100	200	
4	0.00	43.55	46.35	46.38	45.43
	2.50	43.67	46.60	47.18	45.82
	5.00	43.46	46.97	47.02	45.82
6	0.00	43.19	44.72	45.31	44.41
	2.50	43.32	45.14	45.95	44.81
	5.00	43.26	45.02	46.30	44.86
8	0.00	43.23	44.29	45.34	44.29
	2.50	43.22	44.70	45.31	44.41
	5.00	43.50	45.71	45.92	45.04
L.S.D. 0.05			2.442		1.410
Nanochitosan X Irrigation					Irrigation
	4	43.56	46.64	46.86	45.69
	6	43.26	44.96	45.86	44.69
	8	43.32	44.90	45.53	44.58
L.S.D. 0.05			1.410		0.814
Polyter X nanochitosan					Polyter
	0.00	43.33	45.12	45.68	44.71
	2.50	43.41	45.48	46.15	45.01
	5.00	43.41	45.90	46.41	45.24
L.S.D. 0.05			1.410		N.S
Nanochitosan		43.38	45.50	46.08	
L.S.D. 0.05			0.814		

The interaction between irrigation intervals and nano-chitosan also showed significant effects: the treatment combining irrigation every 4 days + nano-chitosan spray at 200 mg·L⁻¹ produced the highest carbohydrate percentage (46.86%), while the lowest value (43.26%) was recorded from the treatment combining irrigation every 6 days + no nano-chitosan spray.

The two-way interaction between polyter and nano-chitosan showed significant differences. The treatment combining nano-chitosan spray at $200 \text{ mg}\cdot\text{L}^{-1}$ + 5 g polyter produced the highest carbohydrate percentage (46.41%), while the lowest value (43.33%) was recorded in the control treatment. Significant differences were also observed in the triple interaction. The treatment combining irrigation every 4 days + 2.5 g polyter + nano-chitosan spray at $200 \text{ mg}\cdot\text{L}^{-1}$ produced the highest carbohydrate percentage (47.18%). In contrast, the lowest value (43.19%) was obtained from the treatment combining irrigation every 6 days + no polyter addition + no nano-chitosan spray.

4. DISCUSSION

The variation in the values of the studied indicators may be attributed to differences in the irrigation intervals adopted in the experiment. The decline in the averages of the studied indicators under irrigation every 8 days could be ascribed to the occurrence of water stress experienced by the growing plants in pot soil, which negatively reflected in the inhibition of cell division and elongation rates, reduction in both absorption and translocation processes, and limitation of stem and leaf expansion. Consequently, root growth parameters decreased, which adversely affected nutrient uptake and reduced their content in plant leaves. In contrast, plants irrigated every 4 days received sufficient moisture, which enhanced the rates and speed of vital processes influencing the growth and development of both shoot and root systems throughout the plant's life cycle. This automatically increased the number and extension of roots, thereby raising the plant's content of nutrients, carbohydrates, and proteins [11], [12]. Relatively frequent irrigation every 4 days provides high and adequate moisture levels for growth, ensuring a nearly continuous water supply to plant cells. This improves and increases the rate of photosynthesis, being the reductive force and primary substrate of the process. Moreover, water directly contributes to the formation of cell protoplasm and cytoplasm, offering a greater opportunity for water storage in plant tissues. Thus, it plays a major role in the synthesis of proteins and carbohydrates. Adequate moisture also enhances enzyme activity and regulates physiological and metabolic processes directly affecting growth. Conversely, irrigation at longer intervals (every 3 days) induces water stress, which negatively impacts leaf expansion and reduces their nutrient content [13], [14]. Similarly, irrigation every 8 days reduces root system activity by hindering growth and slowing cell elongation, rendering roots incapable of absorbing and translocating nutrients to aerial parts of the plant, particularly since sandy soils (Table 1) are characterized by low water-holding capacity [15]. Adequate moisture, in combination with the superabsorbent soil amendment polyter, may improve root growth and development. This positive interaction enhances photosynthesis and accelerates vital processes, ultimately increasing growth rates [16]. The significant improvement in leaf nitrogen and phosphorus content due to polyter addition may be attributed to its ability to retain large amounts of water, maintaining root-zone hydration during drought periods. Its capacity to store and release moisture when needed ensures sustained water availability, while simultaneously improving water relations between soil and plant, thereby facilitating nutrient uptake essential for growth and development ([17]. Regarding chitosan, [18] reported that this compound has recently been widely used to enhance plant tolerance to drought conditions, due to its supply of pectin, which strengthens and reinforces plant cell walls as a structural component, in addition to stimulating growth. Chitosan also participates in the biosynthetic pathway of endogenous hormones (auxins), enhancing the production of tryptophan, the precursor of indole-3-acetic acid (IAA) [19].

Samarfard and Kadir [20] confirmed that chitosan, as an eco-friendly carbohydrate compound, is commonly applied to stimulate the growth of various plant species. El-Hadrami [21] indicated that chitosan improves root system indicators (increasing root number, length, and dry weight), thereby strengthening plant vigor and enhancing nutrient uptake from the soil. Behboudi et al. [22] further emphasized that chitosan is widely applied in agriculture due to its crucial role in protecting plants against different stresses, stimulating growth, acting as an antioxidant, accelerating germination, and improving economic yield. Abdel-Aziz et al. [23] concluded that foliar application of chitosan on plant shoots is easily absorbed through the epidermis, leading to increased growth and productivity in many plants. Notably, chitosan nanoparticles are distinguished by their ability to penetrate plant tissues more effectively than conventional particles, reaching internal sites inaccessible to larger molecules.

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DECLARATION OF COMPETING INTEREST

None

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