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OPTIMIZING WHEAT PRODUCTION: EFFECTS OF ALGINATE OLIGOSACCHARIDE UNDER LIMITED NITROGEN FERTILIZATION

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ABSTRACT

This study investigated the effect of alginate oligosaccharide (Algo) on wheat yield and nitrogen fertilizer optimization over two winter seasons (2020-21 and 2021-22). Algo, an environmentally friendly biostimulant, was applied as a foliar spray during the vegetative growth phase at four different concentrations, in conjunction with three nitrogen application rates-100%, 83%, and 65% of the recommended levels. The results demonstrated that the application of Algo, in combination with nitrogen fertilization, significantly enhanced various agronomic traits, including plant height, spike length, number of spikelets per spike, and the protein and carbohydrate content of wheat grains. Notably, the combination of nitrogen fertilization at 83% and 65% of the recommended rate with a foliar application of 25 mg L^{-1} Algo led to increases in grain yield of approximately 17% and 10%, respectively, compared to the control group receiving 100% nitrogen without Algo. These findings suggest that the application of 25 mg L^{-1} Algo in conjunction with 83% of the recommended nitrogen rate is the most effective treatment. This approach not only reduces nitrogen input but also achieves optimal performance across all measured parameters.

Keywords: Biostimulant, Foliar spray, Fertilization rate, Protein and carbohydrate, Nutritional status, Wheat, Yield

Wheat is a staple food and one of the most widely consumed cereal grains worldwide, recognized for its relatively high protein content compared to other cereals. It serves as a vital source of plant-based protein, along with essential components such as dietary fiber, B vitamins, and various minerals (Hazard *et al.*, 2020). The majority of wheat species belong to the genus *Triticum*, with *Triticum aestivum* (common wheat) being the most extensively cultivated.

The growing global population necessitates a significant increase in wheat production to address the looming threat of food insecurity. In Egypt, for instance, wheat production reached 8.9 million tons per year, while consumption soared to 16 million tons per year, according to the Egyptian Ministry of Agriculture and Land Reclamation (MALR, 2020) (Elsayed *et al.*, 2022; Lamlom *et al.*, 2023). To mitigate the widening gap between consumption and production, increasing wheat output has become a key governmental strategy in Egypt.

Nitrogen is an essential macronutrient that plays a critical role in crop productivity, particularly in wheat cultivation. It is often a limiting factor in wheat production, especially in arid and semi-arid regions (Blumenthal *et al.*, 2008). Consequently, the application of nitrogen fertilizers is crucial in conventional agricultural practices to enhance both yield and yield components (Gomaa *et al.*, 2015; Belete *et al.*, 2018). Nitrogen not only promotes vegetative growth but also improves physiological characteristics and nutritional status, stimulates crop growth rates, and enhances grain yield and quality (Hussain *et al.*, 2006; Abd El-Rheem *et al.*, 2021; Khan *et al.*, 2022). The management of nitrogen fertilizer application is a significant concern for researchers globally, given its economic implications and ecological impacts. Effective control of nitrogen application rates, along with efforts to enhance use efficiency, can mitigate environmental pollution associated with nitrogen losses through volatilization, denitrification, and leaching, while simultaneously increasing wheat yield (Khan *et al.*, 2022; Ali *et al.*, 2000). Integrating growth stimulators and promoting agents into crop production systems presents an indirect strategy to enhance the efficiency of applied fertilizers. These agents can improve nutrient absorption from the soil, thereby supporting overall crop health and productivity (González *et al.*, 2013; Yakhin *et al.*, 2016).

Natural-derived stimulants, commonly known as biostimulants, such as humic acid, fulvic acid, chitosan, polysaccharides, and amino acids, have demonstrated significant potential in the agricultural sector due to their physiological effects on plants and their environmentally friendly nature (Calvo *et al.*, 2014; Halpern *et al.*, 2015; Mahdy *et al.*, 2019). Among these, alginate has emerged as a promising biostimulant with various

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applications across food, biomedical, and industrial fields. Its versatility and efficacy make it an attractive option for enhancing plant growth and productivity in sustainable agricultural practices.

Alginates are primarily derived from natural sources, such as marine algae and certain bacteria, and consist of varying ratios of D-mannuronic acid and L-glucuronic acid (Abd El-Rehim, 2006; Lee and Mooney, 2012; Salachna *et al.*, 2018). While alginates possess high molecular weights, low degradability, and low solubility, these characteristics can limit their practical applications. However, the degradation of alginate into smaller molecular weight compounds has been identified as an effective strategy to overcome these limitations and expand its utility across various fields (Xing *et al.*, 2020).

Alginate oligosaccharide (Algo) is a derivative of alginate degradation, characterized by its low molecular weight. Its biological activity varies significantly depending on its structure and the degradation method used (Abd El-Mohdy, 2017; Zhang *et al.*, 2020). The structural properties of Algo enhance its water solubility compared to alginate, thereby improving its absorption by plants (Ali *et al.*, 2014). Research by Salachna *et al.* (2018) explored the effects of bulb coating of *Eucomis autumnalis*, a medicinal plant, with sodium alginates of varying molecular weights. They found that all tested alginates stimulated plant growth, with the highest growth parameters observed in plants treated with low molecular weight alginate. Furthermore, a recent study highlighted Algo as a growth-promoting factor for various beneficial microorganisms, highlighting its suitability for industrial applications (Le *et al.*, 2022). Algo also serves as a potential growth stimulator for plants, positively influencing the antioxidant system and various biophysical activities, which ultimately enhance growth and yield quality. Soaking wheat and barley seeds in Algo solutions has been shown to improve seed germination, seedling development, and root growth (He *et al.*, 2018; Yang *et al.*, 2021). Additionally, foliar applications of Algo have increased photosynthetic rates and the accumulation of soluble solids and sugars, thereby promoting growth and quality in tea and citrus plants (Hossain *et al.*, 2021; Li *et al.*, 2023). Moreover, Algo has demonstrated significant contributions to plant resistance against various environmental stresses, including heat, drought, salinity, pollution, and irrigation acidity (Liu *et al.*, 2013; Wang *et al.*, 2020; Zhang *et al.*, 2020; Yang *et al.*, 2021; Moussa *et al.*, 2023). This resilience is attributed to Algo's ability to enhance root growth and upregulate resistance-related genes and antioxidant enzymes, such as catalase, superoxide dismutase, and peroxidase.

As the costs of inorganic fertilizers continue to rise, integrating growth-promoting and stimulating agents into agricultural practices offers a promising avenue for enhancing yield production while potentially reducing the quantity of fertilizers applied. In developing countries, improving the efficiency of agricultural inputs and increasing profitability are essential for achieving sustainable agricultural development. Consequently, there is a pressing need for further research on the management of alginate oligosaccharide (Algo) applications and their interactions with fertilization systems.

The primary objective of this study is to evaluate the impact of varying rates of nitrogen fertilizer in conjunction with Algo application on the growth of wheat plants cultivated in loamy sand soil. To achieve this, we test the following hypotheses: I) the application of Algo will enhance the growth parameters, nutritional status, and yield of wheat plants; II) the combination of Algo foliar application with nitrogen fertilization will allow for a reduction in the nitrogen application rate compared to the recommended levels, without compromising yield quantity or quality.

MATERIALS AND METHODS

Description of the study site

A two-year field trial was conducted at the Ismailia Agricultural Research Station, situated at 30° 35' 30" N and 32° 14' 50" E. The study focused on the cultivation of the wheat crop, *Triticum aestivum* L., cultivar Sakha 69, during the winter seasons of 2020-21 and 2021-22. The experimental soil exhibited low organic matter content (0.05%), with available macronutrient levels of nitrogen (N), phosphorus (P), and potassium (K) recorded at 60, 3, and 16 mg kg^{-1}, respectively. The soil was characterized as loamy sand. A summary of the physical and chemical properties of the soil is presented in Table 1.

Experimental design and treatment description

The field experiment was designed as a split-

Table 1. Some physical and chemical characteristics of the experimental soil

Soil texture	$CaCO_3$ (%)	Organic matter (%)	pH (water suspension)	EC (dS m^{-1})	Available macronutrients (mg kg^{-1})		
					N	P	K
Loamy sand	1.9	0.05	8.1	1.2	60	3	16

plot arrangement with four replicates, where nitrogen fertilization constituted the main plots and alginate oligosaccharide (Algo) treatments were randomly assigned to the subplots. Wheat was sown on November 15 and 17 during the first and second seasons, respectively. The study employed four concentrations of Algo (0, 25, 50, and 100 mg L^{-1}) in conjunction with three levels of ammonium nitrate fertilizer (190, 240, and 290 kg N ha^{-1}), which corresponded to 65%, 83%, and 100% of the recommended rate, resulting in a total of 12 treatment combinations.

All agricultural practices were standardized across the experimental units. Each nitrogen fertilizer rate was divided into six equal applications, which were administered biweekly from the time of planting. Algo was sprayed three times during the vegetative growth stage. Standard agricultural practices for wheat cultivation, including irrigation and pest control, were implemented according to the guidelines of the Egyptian Ministry of Agriculture. Additionally, superphosphate fertilizer (15.5% P_2O_5) was applied once at a rate of 71 kg ha^{-1} during soil preparation prior to planting, while potassium fertilizer (potassium sulfate) was applied in two equal doses at planting and during the booting stage (114 kg K_2O ha^{-1}). Wheat harvesting took place on May 6 and 8 in the first and second seasons, respectively.

Plant sampling and analysis

The crop was harvested on May 6 and 8 during the first and second seasons, respectively. For each treatment, a sample of 20 plants was randomly selected to collect data on various growth and yield parameters, including plant height (cm), spike length (cm), number of spikelets per spike, straw yield (ton ha^{-1}), grain yield (ton ha^{-1}), and grain index (g). Grain and straw samples were oven-dried at 65°C for 48 hours. After drying, the samples were ground, and 0.5 g of each was digested using the mixed acids method to determine macronutrient concentrations (Cottenie, 1980).

Nitrogen content was estimated using the Kjeldahl method (Cottenie, 1980). This involved converting nitrogen to ammonia through acid digestion, followed by steam distillation, during which the resulting ammonia was captured in excess boric acid. Phosphorus concentration was determined using the ammonium-vanadate and molybdate method, as described by Motsara and Roy (2008). For potassium determination, the digested samples were analyzed using a flame photometer set specifically for potassium, and the potassium percentage was calculated based on the photometer readings and a calibration curve established with a standard solution (Chapman and Pratt, 1961). Total carbohydrates were assessed on a dry weight basis following the method outlined by Dubois *et al.* (1956). The total protein percentage was estimated by multiplying the nitrogen content by 6.25.

All collected data underwent statistical analysis, and the differences between treatment means were evaluated using Fisher's Least Significant Difference (LSD) at a 0.05 level of probability (Snedecor and Cochran, 1980).

RESULTS AND DISCUSSION

The effects of different concentrations of alginate oligosaccharide (Algo) on agronomic parameters, yield, and nutritional status of wheat plants grown in sandy loam soil under varying levels of nitrogen fertilization are illustrated in Figures 1 and 2, as well as in Tables 2 - 4.

The main effects of nitrogen (N) fertilization rates on the growth, yield, and yield parameters of wheat plants, irrespective of the Algo treatments, are presented in Figure 1. The data represent the average results from two growing seasons, as the values observed during the 2020-21 cropping season were comparable to those in the 2021-22 season. Reducing the amount of N fertilizer from 290 kg ha^{-1} (100% of the recommended rate) to 240 kg ha^{-1} (83% of the recommended) adversely affected all measured growth parameters, including plant height, spike length, and the number of spikelets per spike. This negative impact was further exacerbated by an additional reduction in the fertilization rate to 190 kg ha^{-1} (65% of the recommended rate). Consequently, grain yield reductions of 4.1% and 25% were observed when applying nitrogen at 83% and 65% of the recommended rate, respectively, compared to the yield at the full recommended rate.

The data presented in Figure 2 illustrates the main effects of alginate oligosaccharide (Algo) treatments on wheat yield and growth parameters, represented as mean values across the two seasons. The application of Algo resulted in significant improvements in all studied attributes compared to the control treatment (zero Algo). Specifically, increasing the Algo concentration to 50 mg L^{-1} (50 Algo) led to enhanced growth characteristics and yield values. However, further increasing the Algo concentration to 100 mg L^{-1} (100 Algo) resulted in a decline in these attributes, although the values remained higher than those recorded for the control treatment.

The interaction between foliar application of alginate oligosaccharide (Algo) and various nitrogen fertilization rates had a positive effect on wheat yield and its components, with the data for each growing season summarized in Table 2. Increasing the nitrogen fertilization rate, in conjunction with Algo application at any concentration, significantly enhanced plant height, photosynthetic capacity, spike length, number of spikelets per spike, and grain index compared to treatments without Algo (0 Algo). These parameters

Table 2. The interaction effect of alginate oligosaccharide concentrations (Algo) and nitrogen fertilization rates on growth parameters and yield of wheat plants

N fertilization rate (kg ha^{-1})	Algo (mg l^{-1})	Plant height (cm)	Photo-synthetic capacity* (g/cm^2)	Spike length (cm)	Number of spikelets/ spike	Yield (ton ha^{-1})		Grain index (g)
						Grain	Straw	
First season								
290	0	76.1	4.96	10.5	18.3	5.81	8.24	46.1
	25	80.3	5.42	11.8	22.1	6.74	9.29	48.2
	50	80.2	5.40	11.7	22.0	6.71	9.43	47.9
	100	71.4	4.88	10.4	19.0	5.67	9.17	45.9
240	0	73.1	4.11	10.0	19.0	5.95	8.71	39.2
	25	79.1	4.85	11.6	21.3	6.71	9.10	45.6
	50	79.2	4.82	11.5	21.2	6.69	9.05	45.1
	100	70.2	4.12	10.4	18.8	4.76	8.60	40.2
190	0	52.6	3.44	8.52	14.1	4.12	6.26	38.0
	25	70.7	3.97	10.3	18.3	6.29	8.86	43.5
	50	70.8	3.96	10.2	18.1	6.24	8.93	43.3
	100	65.8	3.51	9.00	15.0	4.50	6.95	39.1
LSD ($p \leq 0.05$)		1.85	0.12	0.67	1.20	0.41	1.31	2.66
Second season								
290	0	76.0	4.95	10.4	18.2	5.74	8.17	46.0
	25	81.4	5.61	11.9	22.3	6.88	9.40	49.1
	50	81.3	5.42	11.8	22.2	6.86	9.38	48.9
	100	72.0	4.98	10.3	19.1	5.48	8.67	46.1
240	0	74.3	4.21	10.6	19.2	5.83	8.21	39.5
	25	80.3	4.91	11.8	22.1	6.76	9.02	46.2
	50	80.2	4.68	11.7	22.1	6.74	9.05	45.8
	100	74.1	4.20	9.11	18.7	4.81	8.62	40.3
190	0	57.9	3.47	7.99	13.9	4.05	6.19	38.1
	25	78.2	4.01	10.8	18.5	6.36	9.00	44.4
	50	77.9	3.97	10.8	18.3	6.31	9.05	44.1
	100	66.5	3.51	8.42	14.4	4.31	6.90	40.0
LSD ($p \leq 0.05$)		1.86	0.12	0.68	1.19	0.43	1.33	2.67

*Photosynthetic capacity = flag leaf weight (g)/flag area (cm^2) (Abd El-Rheem *et al.*, 2021)

exhibited both direct and indirect correlations with grain yield (Mecha *et al.*, 2017). Moreover, under all nitrogen rates, the application of lower Algo concentrations (25 mg L^{-1} and 50 mg L^{-1}) resulted in greater yield parameter values than those recorded with the highest concentration of 100 mg L^{-1}, suggesting an inverse relationship between Algo concentration and the growth attributes measured. This trend was consistent across both growing seasons. Additionally, under the 0 Algo treatment, reducing the nitrogen application rate from 290 to 190 kg ha^{-1} led to a decline in grain yield of approximately 29%. However, this trend was reversed following Algo application; specifically, the foliar application of Algo at 25 mg L^{-1} in combination with a nitrogen rate of 190 kg ha^{-1} increased grain yield by about 9.6% compared to the yield obtained from the 290 kg N ha^{-1} with 0 Algo treatment.

The results presented in Table 3 indicate that the application of alginate oligosaccharide (Algo) at different nitrogen fertilization levels significantly improved the quality of wheat yield by enhancing protein and carbohydrate content in the grains. Generally, lower concentrations of Algo resulted in increased protein and carbohydrate content in both the straw and grains of wheat plants compared to the highest Algo

Table 3. Effect of alginate oligosaccharide concentrations (Algo) and nitrogen fertilization rates on carbohydrate and protein of straw and grains of wheat

N fertilization rate	Algo	First season		Second season	
		Carbohydrate	Protein	Carbohydrate	Protein
(kg ha^{-1})	(mg l^{-1})	(%)		(%)	
Straw					
290	0	14.5	12.9	14.0	12.8
	25	17.0	13.6	17.1	13.5
	50	16.9	13.7	17.0	13.6
	100	14.0	12.7	13.8	12.8
240	0	13.5	11.2	12.8	11.7
	25	16.0	13.4	15.8	13.7
	50	15.8	13.4	18.9	13.6
	100	13.5	12.0	13.4	12.0
190	0	10.1	9.82	9.92	10.0
	25	13.7	12.4	13.4	12.7
	50	13.6	12.1	13.4	12.5
	100	12.0	10.2	11.8	10.5
LSD ($p≤0.05$)		2.1	0.88	2.07	0.9
Grains					
290	0	53.0	16.7	52.9	16.6
	25	60.1	19.8	61.2	19.4
	50	60.0	19.5	61.1	19.1
	100	53.5	17.8	53.1	17.5
240	0	50.0	15.6	49.1	15.8
	25	58.7	18.4	59	18.1
	50	58.0	18.2	58.8	17.9
	100	52.8	17.1	52.5	17.2
190	0	49.7	14.9	48.9	14.8
	25	57.7	17.5	56.8	17.7
	50	56.4	17.1	56.1	17.4
	100	52.2	15.5	50.1	15.8
LSD ($p≤0.05$)		3.5	1.06	3.46	1.1

concentration treatment. The positive effects of Algo were most pronounced at the lowest nitrogen rate of 190 kg ha^{-1}. Under this condition, the application of 25 mg L^{-1} of Algo led to a 1.2- and 1.4-fold increase in carbohydrate content, as well as a 1.2- and 1.3-fold increase in protein content in the grains and straw, respectively, compared to the control treatment (0 Algo) under the same nitrogen fertilization rate.

The results presented in Table 4 illustrate the effects of applying different concentrations of alginate oligosaccharide (Algo) in conjunction with various nitrogen fertilization rates on the nutritional status of wheat plants. Significant enhancements in the nitrogen, phosphorus, and potassium content of wheat leaves were observed following the foliar application of Algo under all nitrogen treatments compared to the control. The increases in nitrogen and phosphorus content were particularly statistically significant. Among the treatments, the combination of 25 mg L^{-1} of Algo with 290 kg N ha^{-1} yielded the highest macronutrient content, highlighting it as the most effective treatment for enhancing the nutritional status of the wheat plants.

The appropriate application of nitrogen, an essential component in the structure of various constituents within plant tissues, is crucial for achieving maximum wheat yields (Ma *et al.*, 2010). The results of this study indicated that applying nitrogen fertilizer at the recommended rate significantly improved wheat yield and all studied

Table 4. **Effect of alginate oligosaccharide concentrations (Algo) and nitrogen fertilization rates on N, P and K content in wheat leaves**

N fertilization rate	Algo	Nutrients content (%)					
		N	P	K	N	P	K
(kg ha^{-1})	(mg l^{-1})	First season			Second season		
290	0	2.66	0.28	2.82	2.64	0.27	2.80
	25	2.81	0.35	2.98	2.80	0.34	2.99
	50	2.80	0.34	2.97	2.79	0.32	2.97
	100	2.76	0.30	2.86	2.75	0.30	2.86
240	0	2.25	0.22	2.76	2.22	0.22	2.75
	25	2.78	0.32	2.92	2.79	0.33	2.91
	50	2.76	0.32	2.90	2.76	0.31	2.91
	100	2.70	0.28	2.85	2.69	0.29	2.84
190	0	1.90	0.20	2.70	1.87	0.21	2.71
	25	2.75	0.32	2.86	2.72	0.33	2.88
	50	2.73	0.31	2.86	2.70	0.32	2.87
	100	2.60	0.27	2.78	2.56	0.26	2.77
LSD ($p \leq 0.05$)		0.10	0.04	0.30	0.11	0.03	0.30

attributes. This finding aligns with the observations of Belete *et al.* (2018) and Khan *et al.* (2022), who examined the influence of nitrogen fertilization rates on different wheat varieties. Furthermore, Abd El Rheem *et al.* (2021) confirmed that the application of nitrogen fertilizer at 290 kg ha^{-1} markedly enhanced the physiological activities and growth of wheat plants, supporting our findings regarding nitrogen fertilization under the zero Algo (0 Algo) treatment.

The combination of different nitrogen rates with foliar application of alginate oligosaccharide (Algo) resulted in significant improvements in all studied growth parameters compared to treatments with nitrogen alone. In the first season, enhancements in grain yield following the application of Algo at 25 mg L^{-1} were observed at rates of 16%, 13%, and 53% under nitrogen rates of 290, 240, and 190 kg ha^{-1}, respectively. In the second season, these enhancements were 20%, 16%, and 57%, respectively. The positive effects of Algo on growth have been documented in the literature, particularly regarding its influence on seedling and root development in crops such as lettuce, carrots, barley, faba bean, and rice (Abd El-Mohdy, 2017; Yang *et al.*, 2021; Iwasaki and Matsubara, 2000; Xu *et al.*, 2003). In a recent study, Liu *et al.* (2022) explored the effects of Algo, alongside other growth regulators, on Chinese milk-vetch plants, confirming that Algo application significantly enhanced pod and seed setting rates, seed number, and seed weight during the squaring stage of development.

During the two growing seasons, no statistically significant differences were observed in the protein and carbohydrate content of straw and grains from plants treated with the lowest nitrogen rate (190 kg ha^{-1}, 65% of the recommended rate) combined with foliar application of Algo (25 mg L^{-1}) compared to those from plants receiving the highest nitrogen rate alone (290 kg ha^{-1}, 100% of the recommended rate). This finding highlights the beneficial role of Algo application. Idrees *et al.* (2015) reported that alginate in its depolymerized form stimulates seed germination and enhances protein content in plants. Furthermore, Yang *et al.* (2021) indicated that the effectiveness of Algo depends on its molecular weights and the Mannuronate/Guluronate ratio, functioning as biostimulants that regulate various physiological and antioxidant activities in plants. He *et al.* (2018) demonstrated that soaking wheat seeds in a solution of 100 µg mL^{-1} calcium alginate microparticles promoted seed germination, improved seedling growth parameters, and increased chlorophyll and soluble protein content; however, increasing the concentration to 500 µg mL^{-1} had a detrimental effect on growth. Additionally, another study found that the application of Algo positively influenced the quality of the productive yield in citrus. Specifically, foliar spraying at concentrations of 300-500 mg L^{-1} enhanced the photosynthetic rate of leaves, as well as the soluble solids and sugar content in the fruits (Li *et al.*, 2023). Our data also indicated an increase in carbohydrate and protein content in wheat straw and grains, despite the applied Algo concentrations (25-100 mg L^{-1}) being significantly lower than those used for citrus and milk-vetch plants. This discrepancy may be attributed to the specific type of plant being studied.

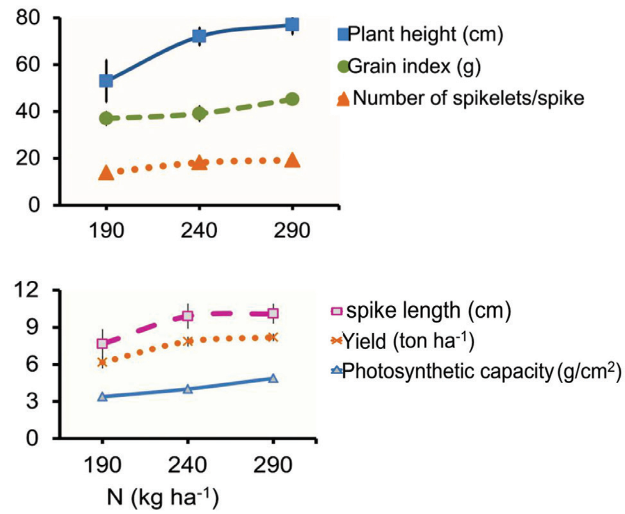

Fig. 1. Main effects of nitrogen fertilization rates on yield and growth parameters of the wheat crop. Data are presented as mean values from two growing seasons, with vertical bars representing standard deviation

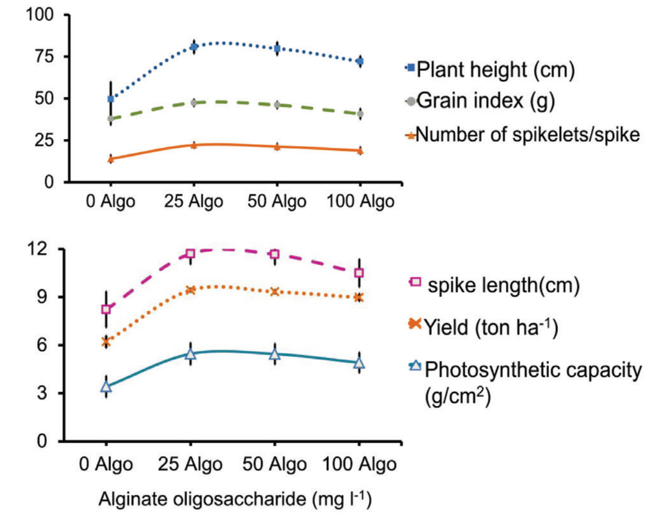

Fig. 2. Main effects of foliar application of alginate oligosaccharide (Algo) on growth parameters and yield of the wheat crop. Data are presented as mean values from two growing seasons. The designations 0 Algo, 25 Algo, 50 Algo, and 100 Algo correspond to the concentrations of sprayed Algo at 0, 25, 50, and 100 mg L⁻¹, respectively. Vertical bars represent the standard deviation

The increase in nutrient concentrations in wheat leaves observed in this study can be attributed to the role of alginate oligosaccharide (Algo) as a biostimulant. Generally, such stimulators promote shoot elongation, root development, and overall growth, including the formation of additional adventitious roots (Li *et al.*, 2023; Taha and Sorour, 2019). This enhanced root structure improves the mobility and translocation of nutrients between plant parts, thereby facilitating greater nutrient absorption (Halpern *et al.*, 2015; He *et al.*, 2018). Consistent with our findings, Wang *et al.* (2020) reported that spraying alginic acid in various diluted solutions significantly improved phosphorus and potassium uptake in radish plants. Additionally, the application of nitrogen fertilizer further contributed to the increased nutrient concentrations, as it promoted root growth and the development of fine roots, potentially enhancing nutrient availability in the soil (Pasley *et al.*, 2019; Chen *et al.*, 2020).

The results of this study suggest that it is possible to reduce nitrogen fertilization rates when applying foliar alginate oligosaccharide (Algo), as the Algo agent helps wheat plants mitigate the negative effects associated with lower nitrogen doses. This approach not only preserves high yield and good quality but also leads to cost reductions, optimized nitrogen utilization, and increased profitability. Furthermore, it minimizes the environmental impact associated with nitrogen loss, as noted by Ali *et al.* (2000).

From an economic perspective, the combination of a low concentration of alginate oligosaccharide (25 mg L^{-1}) with 240 kg N ha^{-1} (83% of the recommended fertilization rate) emerged as the most effective treatment. This approach utilized a lower amount of nitrogen fertilizer compared to the recommended rate of 290 kg ha^{-1}, while still achieving high wheat yields and favourable values for all tested growth parameters.

CONCLUSION

In conclusion, this study highlights the pivotal role of alginate oligosaccharide (Algo) in enhancing wheat production while simultaneously reducing the reliance on nitrogen fertilizers. The foliar application of Algo at a concentration of 25 mg L^{-1} effectively allowed for reductions in nitrogen fertilization rates of 17% to 35% from the recommended levels, without compromising wheat yield. This approach not only optimizes nitrogen utilization but also lowers production costs and enhances profitability for farmers. By integrating Algo into agricultural practices, we can promote sustainable farming while minimizing the environmental impacts associated with excessive nitrogen use. Overall, these findings suggest that Algo presents a viable strategy for improving wheat productivity and sustainability in agricultural systems.

Authors' Contribution

Conceptualization and designing of the research work (DMFM, KhMA); Execution of field experiments (KhMA)/ lab analysis and data collection (DMFM, KhMA); Analysis of data and interpretation (DMFM, KhMA); Preparation of manuscript (DMFM, KhMA).

Conflicts of interest

The authors declare that they have no competing interests or conflicts related to the content of this article. No funding, grants, or other support was received for this study.

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