Growth, Productivity, and Bulb Quality of Two Onion Cultivars as Affected by Foliar Application of Chitosan under Sandy Soil Conditions

Amro I. A. Attia[1], Ahmed A.M. Mohsen[1], Hany G. Zyada[1], Hossam S. El-Beltagi[2*], Adel A. Rezk[2], Wael F. Shehata[2], Ali Osman[3*], Tarek A. Shalaby[4], Ahmed M. Ismail[4], and Enas A. Bardisi[1]

[1] Department of Horticulture, Faculty of Agriculture, Zagazig University, Zagazig, 44519, Egypt; attiaamro9@gmail.com ; Ahmed_mohsen558@yahoo.com ; hjzyada@yahoo.com ; enasbardisi@gmail.com

[2] Agricultural Biotechnology Department, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia; helbeltagi@kfu.edu.sa; arazk@kfu.edu.sa; wshehata@kfu.edu.sa

[3] Department of Biochemistry, Faculty of Agriculture, Zagazig University, Zagazig, 44519, Egypt; aokhalil@zu.edu.eg

[4] Department of Arid Land Agriculture, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia; tshalaby@kfu.edu.sa ; amismail@kfu.edu.sa

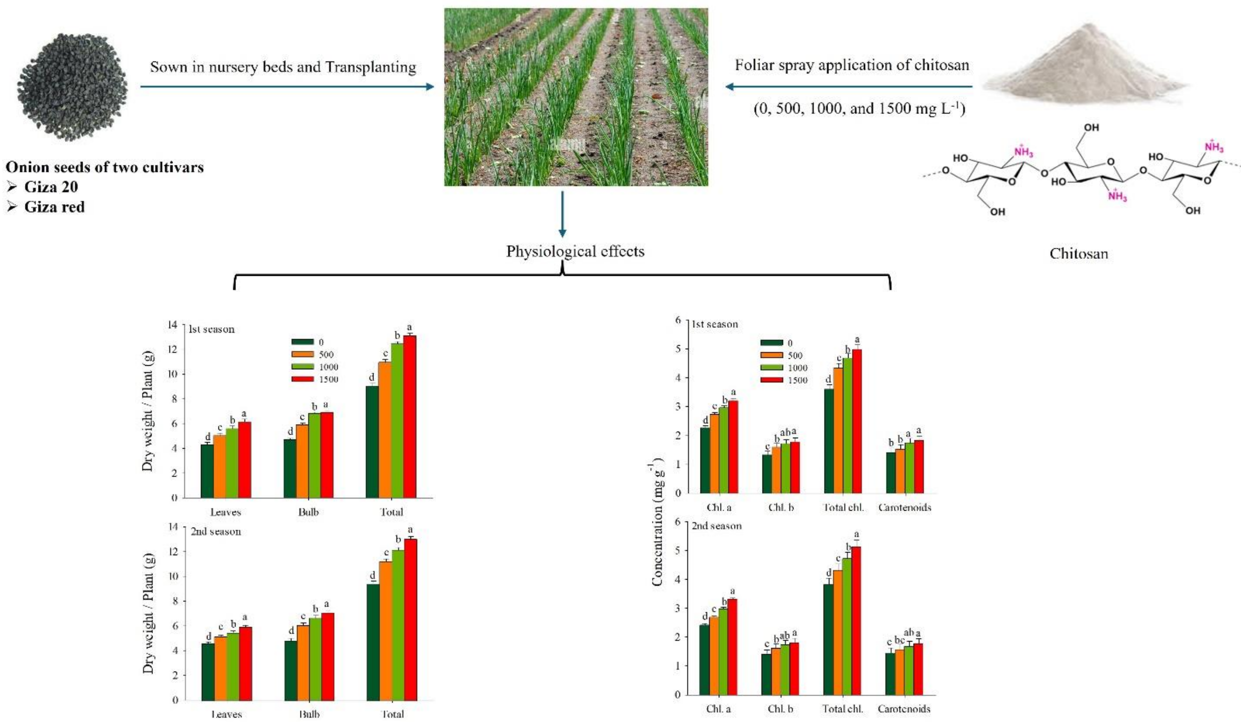
*Correspondence: helbeltagi@kfu.edu.sa. ORCID: https://orcid.org/0000-0003-4433-2034; aokhalil@zu.edu.eg; ORCID: http://orcid.org/0000-0001-7174-0207

Abstract

Effect of foliar application of chitosan on growth, yield, and bulb quality of two onion cultivars were evaluated under sandy soil conditions. Two field experiments were conducted during winter seasons of 2023/2024 and 2024/2025 at El-Saleheya El-Gadida, Sharkia Governorate, Egypt. Four concentrations of chitosan (0, 500, 1000, and 1500 mg L^{-1}) were applied as foliar spray on two onion cultivars (Giza 20 and Giza Red) grown under a drip irrigation system. Growth parameters, yield components, and bulb quality traits were recorded. The interaction between Giza 20 and chitosan at 1500 mg L^{-1} significantly increased leaf, bulb, and total dry weight, as well as chlorophyll (a, b, total) and carotenoids. It also enhanced yield traits, including grade 1 and 2, exportable, marketable, and total yield, in addition to average bulb weight and nitrogen and phosphorus contents. In contrast, Giza Red treated with 1500 mg L^{-1} chitosan showed superior bulb quality, with higher potassium content, total soluble solids (TSS), dry matter, vitamin C, and pungency. Foliar application of chitosan at 1500 mg L^{-1} improves onion growth, productivity, and quality under sandy soil conditions. It represents a sustainable and environmentally friendly strategy that supports efficient resource use and reduces dependence on chemical inputs.

Keywords: Biostimulants, *Allium cepa*, Nutrient uptake, Photosynthetic pigments, Yield components, Soil fertility improvement, Eco-friendly agriculture, Water use efficiency

Graphical abstract



1. Introduction

Onion (*Allium cepa* L.), a member of the Alliaceae family, is one of the most important vegetable and spice crops in Egypt due to its high nutritional, medicinal, and economic value. Onion is widely consumed locally and represents an important export commodity, contributing significantly to farmers' income and the national economy (Shedeed *et al.* 2014). The increasing global demand for fresh, dried, and processed onion products further highlights its agricultural and economic importance. According to the Egyptian Ministry of Agriculture (2024), onion cultivation occupied approximately 333,000 feddans with an average productivity of 15.45 tons per feddan (El Sayed *et al.* 2024).

Despite its economic importance, onion production in newly reclaimed sandy soils remains challenged by low soil fertility, poor water-holding capacity, rapid nutrient leaching, and weak organic matter content (ElGhamry *et al.* 2024). These limitations often encourage excessive application of chemical fertilizers and irrigation water to maintain acceptable productivity levels, leading to increased production costs and potential environmental problems such as soil degradation and nutrient losses. Such practices are inconsistent with current agricultural sustainability goals and environmental management policies that promote efficient use of natural resources and reduction of agrochemical inputs.

Cultivar selection is considered one of the major factors affecting onion growth, productivity, and bulb quality under different environmental conditions. Several studies have demonstrated significant differences among onion cultivars in vegetative growth, yield components, and bulb characteristics (Abou-El-Hassan *et al.* 2018; Demisie and Tolessa, 2018; Gelaye *et al.* 2024; Yeshiwas *et al.* 2024). However, improving onion performance under sandy soil conditions requires not only suitable cultivar selection but also sustainable agronomic practices capable of enhancing plant growth and resource-use efficiency under environmental stress conditions.

In recent years, biostimulants have received increasing attention as eco-friendly alternatives for improving crop productivity and sustainability. Chitosan, a natural biodegradable biopolymer derived from chitin present in fungi and crustacean shells, is widely recognized as an environmentally safe biostimulant (Rai *et al.* 2025). Chitosan has been reported to stimulate plant growth, improve photosynthetic activity, enhance nutrient uptake, activate antioxidant defense systems, and increase plant tolerance to abiotic stresses (Mukarram *et al.* 2023). Moreover, foliar application of chitosan has shown positive effects on yield and quality traits in several horticultural crops, including onion (Sharif *et al.* 2018); Geries *et al.* 2020).

Although previous studies have investigated the beneficial effects of chitosan on onion growth and productivity, limited information is available regarding its effectiveness under sandy soil conditions characterized by low fertility and resource limitations. In addition, insufficient attention has been given to evaluating the interaction between onion cultivars and chitosan concentrations within the framework of sustainable agricultural production and environmental resource management.

Therefore, the present study was conducted to evaluate the effect of foliar application of different chitosan concentrations on growth, productivity, and bulb quality of two onion cultivars grown under sandy soil conditions. The study also aims to identify the most effective chitosan concentration for improving crop performance while supporting sustainable and resource-efficient agricultural practices in newly reclaimed soils.

2. Materials and Methods

2.1. Experimental Conditions

Two field experiments were conducted during winter seasons of 2023/2024 and 2024/2025 at a private farm located in El-Saleheya El-Gadida district, Sharkia Governorate, Egypt. Study assessed foliar chitosan effects on onion growth, yield, and bulb quality under sandy drip-irrigated conditions. Experimental soil was sandy in texture. Soil analysis revealed organic matter content of 0.29% and 0.32%, pH values of 7.98 and 8.01, and electrical conductivity (EC) of 2.19 and 2.01 dS m^{-1} during 1^{st} and 2^{nd} seasons, respectively. Available nutrients were as follows: nitrogen (4.18 and 4.37 mg L^{-1}), phosphorus (3.12 and 3.36 mg L^{-1}), and potassium (10.57 and 10.18 mg L^{-1}).

2.2.*Experimental Design and Treatments*

Experiment consisted of eight treatments arranged in a split-plot design with three replicates. Onion cultivars were assigned to the main plots, while chitosan concentrations were allocated to subplots.

- Factor A (Main plots): Two onion cultivars (Giza 20 and Giza Red)
- Factor B (Subplots): Chitosan concentrations (0, 500, 1000, and 1500 mg L^{-1})

2.3.*Plant Material and Crop Management*

Onion seeds were obtained from the Onion Research Department, Field Crops Research Institute, Agricultural Research Center (ARC), Giza. Seeds were sown in nursery beds on October 20 and 23 in 1^{st} and 2^{nd} seasons, respectively. Transplanting was carried out on December 15 and 17 at a spacing of 10 cm between plants along both sides of the drip irrigation lines.

Each experimental unit covered 10.8 m^2 and consisted of three drip lines (6 m length × 0.60 m width). One line was dedicated to vegetative sampling, while the remaining two lines were used for yield assessment.

Low molecular weight chitosan (degree of deacetylation ≥75%, viscosity 200–800 centipoise cP) was procured from Sigma-Aldrich (St. Louis, MO, USA), and applied as foliar spray at the designated concentrations using a hand sprayer until full leaf wetting. Applications were performed three times at 30, 60, and 90 days after transplanting (DAT) at a rate of 200 L $feddan^{-1}$. Tween-20 (0.02%) was used as a surfactant.

Mineral fertilization included 100 kg N, 60 kg P_2O_5, and 100 kg K_2O per feddan, applied as ammonium sulfate (20.5% N), calcium superphosphate (15.5% P_2O_5), and potassium sulfate (48% K_2O). All phosphorus, one-quarter of nitrogen and potassium, and 20 t $feddan^{-1}$ compost were incorporated during soil preparation. The remaining nitrogen and potassium were applied in five equal doses at two-week intervals starting 30 DAT. Standard agronomic practices were followed throughout the growing seasons.

2.4.Data Collection

2.4.1. Dry Weight Measurements

At 135 days after transplanting, ten plants per plot were sampled. Bulbs and leaves were oven-dried at 70 °C to constant weight, measuring bulb, leaf, and total dry weight per plant.

2.4.2. Photosynthetic Pigments

Leaf samples were collected from the fourth outer leaf to determine chlorophyll a, chlorophyll b, and carotenoids (von Wettstein 1957).

2.4.3. Yield and Yield Components

Harvesting was performed when 50% of tops had fallen. Bulbs were cured in the field for two weeks. Yield was classified based on bulb diameter:

- Grade 1 (>5.5 cm)
- Grade 2 (4.5–5.4 cm)
- Grade 3 (3.5–4.4 cm)
- Grade 4 (<3.5 cm)

Exportable yield included grades 1 and 2, while marketable yield included grades 1, 2, and 3. Total yield comprised all grades. Average bulb weight was calculated based on total yield per plot.

2.4.4. Bulb Quality Parameters

At harvest time (160 days after transplanting), five bulbs per plot were analyzed for:

- N, P, K contents: determined according to standard methods (Jackson 1973; JM 1982; Olsen and Sommers 1983), respectively.
- Dry matter (%): oven drying at 105 °C till constant weight.
- Total soluble solids (TSS): using a ATAGO Hand-Held Refractometer MASTER-53T (°Brix 0-53%)
- Vitamin C: determined using 2,6-dichlorophenol indophenol method (Svehla *et al.* 1963).
- Pungency: measured as pyruvic acid content (Schwimmer and Weston 1961).

2.5.*Statistical Analysis*

Data was analyzed using analysis of variance (ANOVA) appropriate for a split-plot design. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% probability level (Duncan 1955).

3. Results and Discussion

3.1. Dry Weight

3.1.1. Effect of Onion Cultivars

At 135 days after transplanting, significant differences were observed between the two onion cultivars in dry matter accumulation and growth traits (Figure 1). Giza 20 produced higher leaf dry weight, bulb dry weight, and total dry weight per plant than Giza Red in both seasons. The increase in total dry weight of Giza 20 over Giza Red reached 10.06% and 4.55% in the first and second seasons, respectively. The combined mean of both seasons further confirmed the superior vegetative growth performance of Giza 20, which recorded greater plant height, bulb diameter, bulb dry weight, and total dry weight per plant compared with Giza Red. These results indicate that cultivar differences significantly affected biomass accumulation and growth performance under sandy soil conditions. The higher dry matter production observed in Giza 20 may be attributed to genetic differences between cultivars affecting photosynthetic efficiency and assimilate partitioning toward vegetative and bulb growth. Similar varietal differences in onion growth and dry matter accumulation were previously reported by (Kandil *et al.* 2010; Shah *et al.* 2012; Soleymani and Shahrajabian 2012), and (Attia *et al.* 2014), confirming the important role of genotype in determining onion growth and productivity.

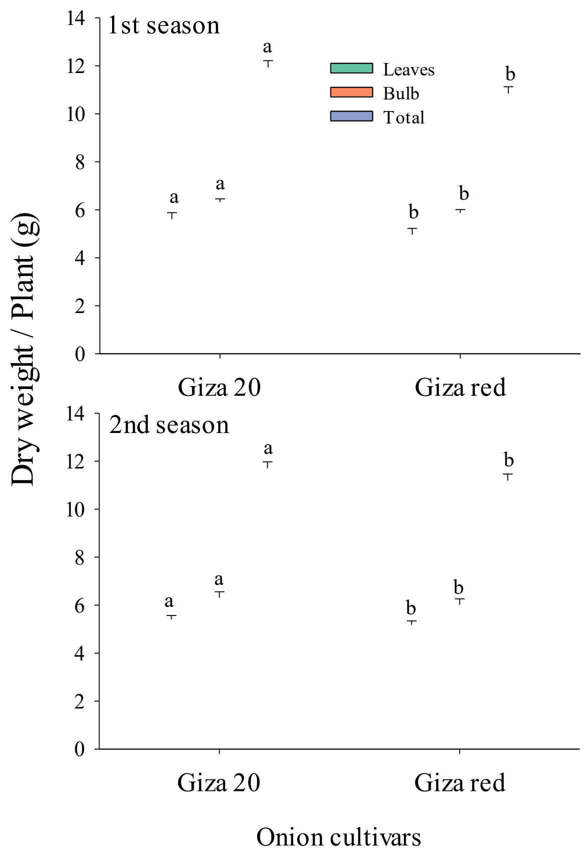


Figure 1. Effect of onion cultivars on dry weight of leaves, bulbs, and total plant (g) after 135 days during the 2023/2024 (1^{st} season) and 2024/2025 (2^{nd} season). Bars represent mean values. Means followed by different letters above bars are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.1.2. Effect of Chitosan Concentration

Foliar application of chitosan significantly enhanced leaf, bulb, and total dry weight of onion plants compared with the untreated control **(Figure 2)**. The promotive effect increased progressively with increasing chitosan concentration, with the highest values consistently recorded at 1500 mg L^{-1}, followed by 1000 mg L^{-1}, in both seasons. Total dry weight increased by 21.22% and 19.09% at 500 mg L^{-1}, 37.46% and 28.84% at 1000 mg L^{-1}, and 44.64% and 38.07% at 1500 mg L^{-1} over the control treatment during the first and second seasons, respectively.

The positive response of onion plants to chitosan application may be associated with improved nutrient assimilation, enhanced nitrogen metabolism, and stimulation of physiological processes involved in plant growth and biomass accumulation (Mondal *et al.* 2012). Chitosan has also been reported to promote photosynthetic activity and enhance the availability of amino compounds (Chibu 2001; Hadwiger *et al.* 2002). which contribute to improved vegetative growth and dry matter production. The progressive increase in dry weight with increasing chitosan concentration suggests a strong stimulatory effect of chitosan on biomass accumulation u der sandy soil conditions. These results agree with previous findings reported by (Battikha *et al.* 2020), who observed significant increases in onion dry weight with higher chitosan concentrations. Similar positive effects of chitosan on onion growth and dry matter accumulation were also reported by (Geries *et al.* 2020; Ray *et al.* 2023).

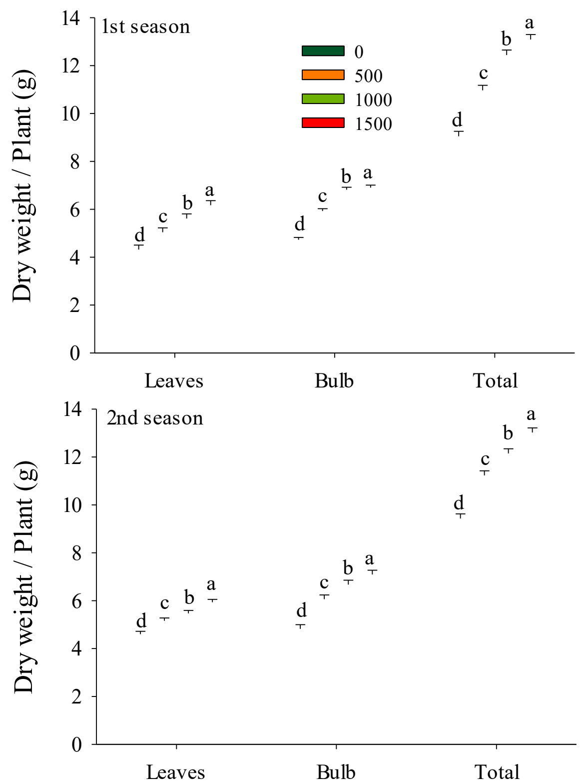


Figure 2. Effect of foliar application of chitosan at different concentrations (0, 500, 1000, and 1500 mg L^{-1}) on dry weight of leaves, bulbs, and total dry weight per plant (g) of onion after 135 days during the 2023/2024 (1st season) and 2024/2025 (2nd season). Bars represent mean values. Means followed by different letters above bars are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.1.3. Effect of Interaction

The interaction between Giza 20 and foliar application of chitosan at 1500 mg L^{-1} produced the highest dry matter accumulation among all treatment combinations **(Table 1)**. This treatment significantly increased leaf dry weight, bulb dry weight, and total dry weight per plant in both seasons compared with the other interactions. Total dry weight under this combination exceeded that of Giza Red treated with the same chitosan concentration by 9.44% and 6.58% in the first and second seasons, respectively.

The superior response of Giza 20 to the highest chitosan concentration indicates a positive interaction between cultivar characteristics and chitosan application under sandy soil conditions. Improved vegetative growth traits, particularly plant height, leaf development, and bulb growth, likely contributed to greater biomass accumulation and dry matter production. These findings suggest that chitosan application at 1500 mg L^{-1} effectively enhanced the growth potential of Giza 20, resulting in improved plant vigor and total dry matter accumulation.

Table 1. Effect of interaction between onion cultivars and foliar application of chitosan concentrations on dry weight of leaves, bulb, and total dry weight per plant (g) at 135 days after transplanting during 2023/2024 and 2024/2025 seasons.

Treatments		**Dry weight / Plant (g)**		
		Leaves	**Bulb**	**Total (leaves+ bulb)**
Cultivars	Chitosan (mg L^{-1})		2023/2024	
Giza 20	0	4.68^{d}	4.94^{f}	9.62^{g}
	500	5.44^{c}	6.04^{d}	11.48^{e}
	1000	5.88^{b}	7.08^{b}	12.96^{b}
	1500	6.45^{a}	7.23^{a}	13.68^{a}
Giza Red	0	3.96^{e}	4.52^{g}	8.48^{h}
	500	4.64^{d}	5.82^{e}	10.46^{f}
	1000	5.36^{c}	6.56^{c}	11.92^{d}
	1500	5.90^{b}	6.60^{c}	12.50^{c}
			2024/2025	
Giza 20	0	4.89^{e}	5.04^{d}	9.93^{f}
	500	5.27^{cd}	6.18^{c}	11.45^{d}
	1000	5.41^{bc}	6.64^{b}	12.05^{c}
	1500	6.03^{a}	7.41^{a}	13.44^{a}
Giza Red	0	4.32^{f}	4.61^{e}	8.93^{g}
	500	5.06^{de}	5.95^{c}	11.01^{e}
	1000	5.54^{b}	6.71^{b}	12.25^{c}
	1500	5.83^{a}	6.78^{b}	12.61^{b}

Means followed by different letters within the same column are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.2. Leaf Photosynthetic Pigments

3.2.1. Effect of Onion Cultivars

Results presented in **Figure 3** showed that Giza 20 cultivar had higher chlorophyll a and total chlorophyll (a + b) content in leaf tissues than Giza Red at 135 days after transplanting in both seasons. In contrast, chlorophyll b and carotenoid contents were not significantly affected by cultivar differences. The increase in total chlorophyll content of Giza 20 over Giza Red was 10.79% and 8.10% in the first and second seasons, respectively.

These differences in chlorophyll accumulation suggest that Giza 20 possesses a higher photosynthetic pigment potential under sandy soil conditions, which may contribute to improved growth performance. The variation between cultivars is mainly attributed to genetic factors controlling pigment synthesis and accumulation in leaf tissues. Similar cultivar-dependent differences in chlorophyll content have been reported by (Geries *et al.* 2012; Kandil *et al.* 2013), and (Ratan *et al.* 2017), confirming that leaf pigment variation in onion is largely genotype dependent.

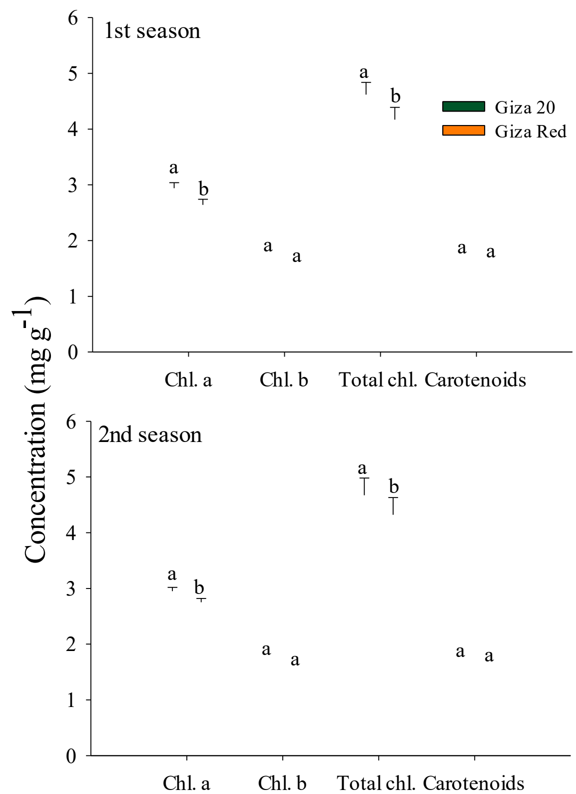


Figure 3. Effect of onion cultivars on chlorophyll a (chl. a), chlorophyll b (chl. b), Total chlorophyll (a and b), and carotenoids (mg g^{-1}) after 135 days during the 2023/2024 (1st season) and 2024/2025 (2nd season). Bars represent mean values. Means followed by different letters above bars are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.2.2. Effect of Chitosan Concentration

Foliar application of chitosan significantly increased chlorophyll a, chlorophyll b, total chlorophyll (a + b), and carotenoid contents in onion leaves at 135 days after transplanting, particularly at the highest concentration (1500 mg L^{-1}) **(Figure 4)**. Total chlorophyll content increased by 20.28% and 12.83% at 500 mg L^{-1}, 30.00% and 23.56% at 1000 mg L^{-1}, and 38.33% and 34.29% at 1500 mg L^{-1} compared with the control in the first and second seasons, respectively.

The improvement in photosynthetic pigments with chitosan application may be associated with its role in stimulating physiological processes involved in chlorophyll biosynthesis, including the enhancement of endogenous growth regulators such as cytokinins. Increased pigment content likely contributed to improved photosynthetic efficiency, which in turn supported better plant growth and productivity under sandy soil conditions (Chibu 2001).

These findings are consistent with previous studies reporting positive effects of chitosan on leaf pigment content in different crops, including bean (Sheikha and Al-Malki 2011) and radish (Farouk *et al.* 2011). Similar results were also reported by (Roshdy and Khadr 2023), who found that foliar application of chitosan enhanced chlorophyll content in onion compared with untreated plants.

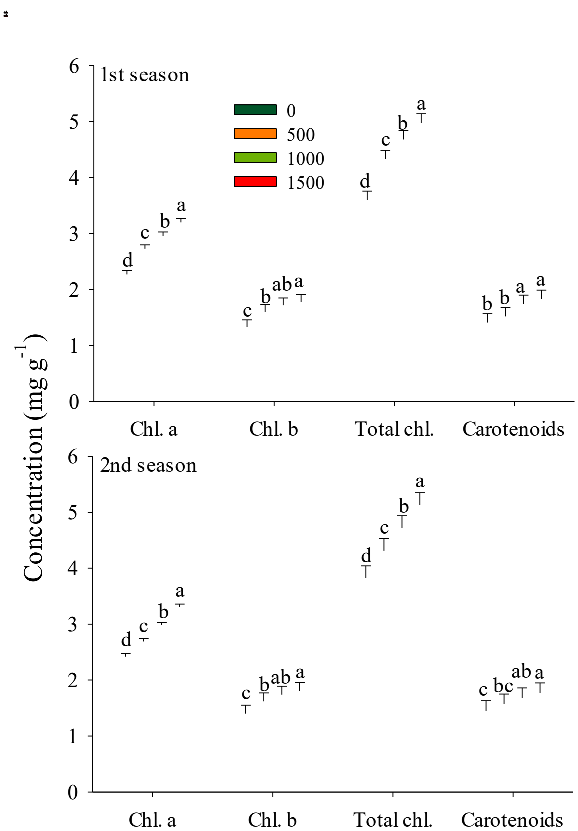


Figure 4. Effect of foliar application of chitosan at different concentrations (0, 500, 1000, and 1500 mg L⁻¹) on chlorophyll a (chl. a), chlorophyll b (chl. b), Total chlorophyll (a and b), and carotenoids (mg g^{-1}) of onion after 135 days during the 2023/2024 (1^{st} season) and 2024/2025 (2^{nd} season). Bars represent mean values. Means followed by different letters above bars are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.2.3. Effect of Interaction

The interaction between Giza 20 and foliar application of chitosan at 1500 mg L^{-1} recorded the highest chlorophyll a, chlorophyll b, total chlorophyll (a + b), and carotenoid contents in onion leaves at 135 days after transplanting in both seasons **(Table 2)**. Total chlorophyll content under this interaction was higher by 11.68% and 10.68% compared with the interaction between Giza Red and chitosan at the same concentration in the first and second seasons, respectively.

This superior performance indicates a synergistic effect between the genetic potential of Giza 20 and the physiological stimulation induced by chitosan, leading to enhanced pigment biosynthesis and improved photosynthetic capacity. Increased chlorophyll content under this treatment combination likely contributed to better plant growth and productivity under sandy soil conditions.

These findings are in agreement with (Amjad *et al.* 2024), who reported that foliar application of chitosan significantly improved chlorophyll content in onion, confirming its positive role in enhancing leaf pigment composition.

Table 2. Effect of interaction between and foliar application of chitosan concentrations on chlorophyll a (chl. a), chlorophyll b (chl. b), Total chlorophyll (a and b), and carotenoids (mg g^{-1}) at 135 days after transplanting during the 2023/2024 and 2024/2025 seasons.

Treatments		**Concentration (mg $^{g-1}$)**			
		Chl. a	**Chl. b**	**Total chl.**	**Carotenoids**
Cultivars	Chitosan (mg L⁻¹)	2023/2024			
Giza 20	0	2.36^{f}	1.36^{de}	3.72^{f}	1.45^{cd}

	500	2.85^{d}	1.67^{bc}	4.52^{cd}	1.59^{bcd}
	1000	3.17^{b}	1.83^{ab}	5.00^{b}	1.76^{ab}
	1500	3.38^{a}	1.88^{a}	5.26^{a}	1.89^{a}
Giza Red	0	2.18^{g}	1.30^{e}	3.48^{f}	1.38^{d}
	500	2.61^{e}	1.54^{cd}	4.15^{e}	1.45^{d}
	1000	2.75^{d}	1.61^{bc}	4.36^{de}	1.72^{abc}
	1500	3.02^{c}	1.69^{abc}	4.71^{c}	1.78^{ab}
			2024/2025		
Giza 20	0	2.55^{e}	1.45^{cd}	4.00^{de}	1.49^{bc}
	500	2.65^{d}	1.71^{ab}	4.36^{c}	1.61^{abc}
	1000	3.12^{b}	1.83^{a}	4.95^{b}	1.69^{abc}
	1500	3.50^{a}	1.89^{a}	5.39^{a}	1.82^{a}
Giza Red	0	2.29^{f}	1.35^{d}	3.64^{e}	1.42^{c}
	500	2.74^{d}	1.53^{bcd}	4.27^{cd}	1.54^{abc}
	1000	2.85^{c}	1.65^{abc}	4.50^{c}	1.67^{abc}
	1500	3.13^{b}	1.74^{ab}	4.87^{b}	1.73^{ab}

Means followed by different letters within the same column are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.3. Yield and Its Components

3.3.1. Effect of Onion Cultivars

Data presented in **Table 3** showed significant differences between the two onion cultivars in yield and yield components during both seasons. Giza 20 consistently produced higher yields of grade 1 and grade 2 bulbs, resulting in greater exportable, marketable, and total yields compared with Giza Red. It also recorded a higher average bulb weight. In contrast, Giza Red produced a greater proportion of lower-grade bulbs (grades 3 and 4).

The combined analysis of both seasons confirmed the superiority of Giza 20 under sandy soil conditions. The higher proportion of premium bulbs in Giza 20 contributed to increased exportable and marketable yields, indicating better bulb quality and commercial value. Conversely, Giza Red showed a relatively higher percentage of small-sized bulbs, which reduced its overall marketable performance.

The variation between cultivars in bulb grading and yield performance may be attributed to genetic differences affecting growth efficiency, assimilate partitioning, and adaptation to sandy soil conditions. The superior productivity of Giza 20 was associated with improved vegetative growth and greater dry matter accumulation, which likely enhanced bulb development and yield formation. These findings are consistent with previous studies by (Geries *et al.* 2012; Kandil *et al.* 2013; Soleymani and Shahrajabian 2012), and (Abou-El-Hassan *et al.* 2018), who reported significant varietal differences in onion yield and bulb characteristics.

Table 3. Effect of onion cultivars on yield and its components of onion plants during the 2023/2024 (1st season) and 2024/2025 (2nd season).

Treatments	**Grade (ton/fed.)**				**Ton /fed.**			**Bulb weight (g)**
	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Exportable yield**	**Marketable yield**	**Total yield**	
Cultivars					2023/2024			
Giza 20	7.177^{a}	5.970^{a}	1.808^{b}	0.742^{b}	13.147^{a}	14.956^{a}	15.699^{a}	111.09^{a}
Giza Red	3.973^{b}	4.711^{b}	2.886^{a}	1.121^{a}	9.435^{b}	11.572^{b}	12.693^{b}	90.23^{b}
					2024/2025			
Giza 20	6.835^{a}	5.651^{a}	1.710^{b}	1.099^{b}	12.488^{a}	14.198^{a}	15.298^{a}	108.93^{a}
Giza Red	4.732^{b}	5.455^{a}	2.120^{a}	1.423^{a}	10.938^{b}	12.308^{b}	13.731^{b}	97.36^{b}

Means followed by different letters within the same column are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.3.2. Effect of Chitosan Concentration

Foliar application of chitosan significantly improved onion yield and its components compared with the untreated control **(Table 4).** The positive effect increased with increasing chitosan concentration, with 1500 mg L^{-1} producing the highest values for grade 1 and grade 2 yields, exportable yield, marketable yield, total yield, and average bulb weight in both seasons. In contrast, the control treatment recorded the highest proportion of grade 4 bulbs, while the lower chitosan concentration (500 mg L^{-1}) produced relatively higher grade 3 yield.

Total yield increased by 20.00% and 8.28% at 500 mg L^{-1}, 33.25% and 39.04% at 1000 mg L^{-1}, and 40.39% and 46.95% at 1500 mg L^{-1} over the control treatment in the first and second seasons, respectively. The increase in marketable and exportable yields under chitosan application reflects the improvement in bulb size and quality.

The enhancement in yield performance may be associated with the positive effects of chitosan on vegetative growth, dry matter accumulation, and photosynthetic pigment content, which collectively improved photosynthetic efficiency and assimilate translocation toward bulb development. The superior performance at 1500 mg L^{-1} suggests that this concentration was most effective in promoting growth and productivity under sandy soil conditions.

These findings agree with previous reports by (Fawzy *et al.* 2012; Ray *et al.* 2023; Roshdy and Khadr 2023; Battikha *et al.* 2020) and Amjad *et al.* (2024), who also observed significant improvements in onion yield and bulb characteristics following foliar application of chitosan.

Table 4. Effect of foliar application of chitosan on yield and its components of onion plants during the 2023/2024 (1st season) and 2024/2025 (2nd season).

Treatments	**Grade (ton/fed.)**				**Ton /fed.**			**Bulb weight (g)**
	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Exportable yield**	**Marketable yield**	**Total yield**	
Chitosan (mg L^{-1})				2023/2024				
0	4.505^{d}	3.581^{d}	2.275^{b}	1.140^{a}	8.087^{d}	10.363^{d}	11.503^{d}	81.27^{d}
500	5.062^{c}	5.310^{c}	2.379^{ab}	1.052^{b}	10.872^{c}	12.752^{c}	13.804^{c}	98.31^{c}
1000	6.031^{b}	6.022^{b}	2.426^{a}	0.848^{c}	12.553^{b}	14.480^{b}	15.328^{b}	108.68^{b}
1500	6.702^{a}	6.450^{a}	2.309^{ab}	0.688^{d}	13.653^{a}	15.462^{a}	16.149^{a}	114.38^{a}
				2024/2025				
0	4.075^{c}	4.117^{d}	1.974^{a}	1.579^{a}	8.192^{d}	10.166^{d}	11.746^{d}	83.27^{d}
500	4.850^{b}	4.371^{c}	2.013^{a}	1.484^{b}	9.722^{c}	11.235^{c}	12.719^{c}	90.70^{c}
1000	6.910^{a}	6.501^{b}	1.858^{b}	1.063^{c}	13.912^{b}	15.270^{b}	16.332^{b}	116.02^{b}
1500	7.300^{a}	7.225^{a}	1.816^{b}	0.919^{d}	15.025^{a}	16.342^{a}	17.261^{a}	122.60^{a}

Means followed by different letters within the same column are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.3.3. Effect of Interaction

The interaction between Giza 20 and foliar application of chitosan at 1500 mg L^{-1} produced the highest yield and yield components among all treatment combinations **(Table 5)**. This treatment significantly increased grade 1 and grade 2 yields, exportable yield, marketable yield, total yield, and average bulb weight in both seasons. In contrast, Giza Red combined with either the control treatment or the lower chitosan concentration (500 mg L^{-1}) produced higher proportions of grade 3 and grade 4 bulbs.

The superior performance of Giza 20 under the highest chitosan concentration indicates a strong positive interaction between cultivar potential and chitosan application in improving bulb development and marketable yield under sandy soil conditions. The increase in bulb weight and premium-grade yield was likely associated with enhanced vegetative growth, dry matter accumulation, and photosynthetic activity observed under this treatment combination.

These findings suggest that foliar application of chitosan at 1500 mg L^{-1} was particularly effective in maximizing the productivity and bulb quality of Giza 20. Similar positive interactions between chitosan application and cultivar performance were reported by Tantawy *et al.* (2021), who found that chitosan at 1500 mg L^{-1} significantly improved garlic yield compared with untreated plants. Data presented in **Table 6** showed that total onion yield was positively correlated with total dry weight per plant, leaf chlorophyll content, and average bulb weight.

Table 5. Effect of interaction between onion cultivars and foliar application of chitosan on yield and its components of onion plants during the 2023/2024 (1st season) and 2024/2025 (2nd season).

Treatments		Grade (ton/fed.)				Ton /fed.			Bulb weight (g)
		Grade 1	Grade 2	Grade 3	Grade 4	Exportable yield	Marketable yield	Total yield	
Cultivars	Chitosan (mg L⁻¹)	2023/2024							
Giza 20	0	5.742^{c}	4.011^{d}	1.629^{e}	1.089^{bc}	9.753^{d}	11.382^{e}	12.471^{d}	88.08^{f}
	500	6.250^{c}	5.905^{b}	1.665^{e}	0.982^{d}	12.155^{c}	13.820^{c}	14.802^{b}	104.73^{c}
	1000	7.767^{b}	6.946^{a}	1.959^{d}	0.678^{e}	14.713^{b}	16.672^{b}	17.350^{a}	123.12^{b}
	1500	8.950^{a}	7.019^{a}	1.980^{d}	0.222^{f}	15.969^{a}	17.949^{a}	18.171^{a}	128.43^{a}
Giza Red	0	3.269^{e}	3.152^{e}	2.922^{ab}	1.191^{a}	6.421^{e}	9.343^{f}	10.534^{e}	74.46^{g}
	500	3.875^{de}	4.715^{c}	3.093^{a}	1.123^{ab}	9.590^{d}	11.683^{e}	12.806^{d}	91.88^{e}
	1000	4.295^{d}	5.098^{c}	2.894^{b}	1.018^{cd}	10.393^{d}	12.287^{de}	13.305^{cd}	94.24^{e}
	1500	4.454^{d}	5.882^{b}	2.638^{c}	1.154^{ab}	11.336^{c}	12.974^{cd}	14.128^{bc}	100.33^{d}
		2024/2025							
Giza 20	0	4.678^{d}	4.010^{e}	1.828^{c}	1.504^{c}	8.688^{ef}	10.516^{e}	12.020^{fg}	85.36^{g}
	500	5.935^{c}	4.099^{e}	1.823^{c}	1.194^{d}	10.034^{d}	11.857^{d}	13.051^{e}	93.12^{e}
	1000	7.948^{b}	6.941^{b}	1.701^{c}	0.952^{e}	14.889^{b}	16.590^{b}	17.542^{b}	125.02^{b}
	1500	8.782^{a}	7.557^{a}	1.491^{d}	0.749^{f}	16.339^{a}	17.830^{a}	18.579^{a}	132.22^{a}
Giza Red	0	3.472^{e}	4.224^{e}	2.120^{ab}	1.655^{b}	7.696^{f}	9.816^{e}	11.471^{g}	81.17^{h}
	500	3.765^{e}	4.644^{d}	2.203^{a}	1.775^{a}	9.409^{de}	10.612^{e}	12.387^{ef}	88.28^{f}
	1000	5.873^{c}	6.061^{c}	2.016^{b}	1.175^{d}	12.934^{c}	13.950^{c}	15.122^{d}	107.01^{d}
	1500	5.819^{c}	6.893^{b}	2.141^{ab}	1.090^{de}	13.712^{c}	14.853^{c}	15.943^{c}	112.98^{c}

Means followed by different letters within the same column are significantly different at P ≤ 0.05 according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

Table 6. Correlation coefficients among total yield, total dry weight, leaf chlorophyll content, and average bulb weight of onion plants as influenced by the interaction between cultivars and foliar application of chitosan (mean of 2023/2024 and 2024/2025 seasons).

Treatments	Total dry weight (g)	Total chlorophyll (a+b) mg/g fresh weight	Average bulb weight (g)
Total yield (ton/fed.)	0.92	0.97	1.00
Total dry weight (g)		0.98	0.93
Total Chl.			0.97
Average bulb weight (g)			

3.4. Bulb Quality

3.4.1. Effect of Onion Cultivars

Significant differences were observed between Giza 20 and Giza Red cultivars in several bulb quality traits during both seasons **(Table 7)**. Giza Red recorded higher values of potassium (K), total soluble solids (TSS), dry matter (DM), vitamin C, and pungency compared with Giza 20, whereas Giza 20 showed higher phosphorus (P) content in bulbs. In contrast, nitrogen content was not significantly affected by cultivar.

The combined mean of both seasons confirmed the superiority of Giza Red in bulb quality characteristics, particularly dry matter, vitamin C, and pungency, indicating its potential for improved bulb quality under sandy soil conditions. The observed differences between cultivars are mainly attributed to genetic variation affecting nutrient accumulation and bulb biochemical composition. These findings are consistent with previous studies by (Demisie and Tolessa 2018; Geries *et al.* 2012), and (Marey and Morsy 2010), who also reported significant cultivar-dependent variation in onion bulb quality traits.

Table 7. Effect of onion cultivars on bulb quality at harvesting time of onion plants during 2023/2024 and 2024/2025 seasons

Treatments	Mineral contents (%)			TSS	DM (%)	Vit C (mg/100 ml Juice)	Pungency as pyruvic acid µmol/gm FW
	N	P	K				
Cultivars				2023/2024			
Giza 20	1.71ᵃ	0.429ᵃ	1.48ᵇ	11.01ᵇ	12.10ᵇ	16.42ᵇ	6.87ᵇ
Giza Red	1.64ᵃ	0.398ᵇ	1.60ᵃ	11.68ᵃ	12.71ᵃ	17.33ᵃ	8.17ᵃ
				2024/2025			
Giza 20	1.71ᵃ	0.431ᵃ	1.45ᵇ	11.64ᵇ	12.99ᵇ	16.13ᵇ	6.64ᵇ
Giza Red	1.60ᵃ	0.391ᵇ	1.61ᵃ	12.58ᵃ	13.61ᵃ	17.09ᵃ	8.46ᵃ

Means followed by different letters within the same column are significantly different at P ≤ 0.05 according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.4.2. Effect of Chitosan Concentration

Foliar application of chitosan significantly enhanced bulb quality traits, including N, P, K, TSS, dry matter, vitamin C, and pungency, compared with the control treatment **(Table 8)**. The highest values were consistently obtained with chitosan at 1500 mg L^{-1} in both seasons.

The improvement in bulb quality may be associated with the positive effects of chitosan on nutrient uptake (Guan *et al.* 2009), water utilization (Chibu 2001), and physiological activity (Boßelmann *et al.* 2007), which enhanced bulb development and biochemical composition. Chitosan may also improve antioxidant activity and cellular protection (Sun *et al.* 2008), contributing to higher accumulation of soluble solids, dry matter, and vitamin C in onion bulbs. The superior response observed at 1500 mg L^{-1} indicates that this concentration was the most effective in improving bulb nutritional and quality characteristics under sandy soil conditions. Similar improvements in onion bulb quality following chitosan application were previously reported by (Geries *et al.* 2020).

Table 8. Effect of foliar application of chitosan on bulb quality at harvesting time of onion plants during 2023/2024 and 2024/2025 seasons

Treatments	Mineral contents (%)			TSS	DM (%)	Vit C (mg/100 ml Juice)	Pungency as pyruvic acid µmol/gm FW
	N	P	K				
Chitosan (mg L^{-1})				2023/2024			
0	1.50^{c}	0.375^{c}	1.40^{c}	10.07^{d}	11.25^{d}	15.15^{d}	6.48^{d}
500	1.62^{b}	0.411^{b}	1.55^{b}	11.17^{c}	12.46^{c}	17.08^{c}	7.21^{c}
1000	1.77^{a}	0.432^{a}	1.59^{ab}	11.86^{b}	12.73^{b}	17.47^{b}	7.99^{b}
1500	1.82^{a}	0.437^{a}	1.63a	12.29^{a}	13.17^{a}	17.81^{a}	8.42^{a}
				2024/2025			
0	1.47^{c}	0.381^{d}	1.40^{d}	10.76^{d}	11.71^{d}	14.94^{d}	6.50^{d}
500	1.65^{b}	0.400^{c}	1.51^{c}	11.91^{c}	13.33^{c}	16.90^{c}	7.50^{c}
1000	1.72^{ab}	0.426^{b}	1.57^{b}	12.72^{b}	14.00^{b}	17.12^{b}	8.01^{b}
1500	1.78^{a}	0.436^{a}	1.64^{a}	13.04^{a}	14.15^{a}	17.48^{a}	8.21^{a}

Means followed by different letters within the same column are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

3.4.3. *Effect of Interaction*

Data presented in Table 9 showed significant interaction effects between onion cultivars and chitosan concentrations on bulb quality traits. The interaction between Giza 20 and chitosan at 1000 or 1500 mg L^{-1} resulted in higher N and P contents in bulbs. In contrast, Giza Red combined with chitosan at 1500 mg L^{-1} produced the highest values of K, TSS, dry matter, vitamin C, and pungency in both seasons.

The variation among interaction treatments indicates that cultivar response to chitosan differed according to the quality trait evaluated. Giza Red showed superior bulb quality characteristics under the highest chitosan concentration, whereas Giza 20 responded more positively in terms of nutrient accumulation.

In addition, positive correlations were observed between dry matter and both TSS and pungency, suggesting that increased dry matter accumulation was associated with improved bulb quality attributes. These results demonstrate the beneficial role of chitosan, particularly at 1500 mg L^{-1}, in enhancing onion bulb quality under sandy soil conditions.

Table 9. Effect of interaction between onion cultivars and foliar application of chitosan concentrations on bulb quality at harvesting time of onion plants during 2023/2024 and 2024/2025 seasons

Treatments		**Mineral contents (%)**			**TSS**	**DM (%)**	**Vit C (mg/100 ml Juice)**	**Pungency as pyruvic acid µmol/gm FW**
Cultivars	Chitosan (mg L^{-1})	**N**	**P**	**K**				
		2023/2024						
Giza 20	0	1.51^{e}	0.407^{cd}	1.35^{f}	9.92^{g}	10.88^{g}	14.26^{g}	5.90^{h}
	500	1.66^{cd}	0.425^{bc}	1.49^{de}	10.96^{e}	12.23^{e}	16.70^{e}	6.18^{g}
	1000	1.81^{ab}	0.439^{ab}	1.54^{cde}	11.37^{d}	12.35^{e}	17.23^{d}	7.42^{e}
	1500	1.87^{a}	0.448^{a}	1.57^{bcd}	11.79^{c}	12.94^{c}	17.51^{bc}	8.00^{d}
Giza Red	0	1.49^{e}	0.344^{e}	1.46^{e}	10.23^{f}	11.62^{f}	16.05^{f}	7.06^{f}
	500	1.59^{de}	0.398^{d}	1.62^{abc}	11.38^{d}	12.70^{d}	17.47^{cd}	8.24^{c}
	1000	1.73^{bc}	0.425^{bc}	1.65^{ab}	12.35^{b}	13.12^{b}	17.71^{b}	8.56^{b}
	1500	1.77^{abc}	0.426^{bc}	1.69^{a}	12.79^{a}	13.40^{a}	18.11^{a}	8.84^{a}
		2024/2025						

Giza 20	0	1.54^{cd}	0.403^{c}	1.33^{e}	10.37^{h}	10.95^{f}	14.13^{g}	5.38^{f}
	500	1.68^{b}	0.427^{b}	1.45^{d}	11.45^{f}	13.03^{d}	16.54^{e}	6.68^{e}
	1000	1.77^{ab}	0.441^{a}	1.48^{d}	12.19^{e}	13.88^{b}	16.76^{d}	7.17^{d}
	1500	1.85^{a}	0.453^{a}	1.55^{c}	12.55^{c}	14.10^{a}	17.11^{c}	7.36^{d}
Giza Red	0	1.41^{d}	0.359^{e}	1.48^{d}	11.15^{g}	12.47^{e}	15.75^{f}	7.62^{c}
	500	1.63^{bc}	0.374^{d}	1.58^{c}	12.38^{d}	13.64^{c}	17.26^{c}	8.32^{b}
	1000	1.67^{bc}	0.412^{bc}	1.66^{b}	13.26^{b}	14.13^{a}	17.49^{b}	8.86^{a}
	1500	1.71^{ab}	0.420^{b}	1.73^{a}	13.54^{a}	14.21^{a}	17.86^{a}	9.06^{a}

Means followed by different letters within the same column are significantly different at $P \leq 0.05$ according to Duncan's Multiple Range Test (DMRT). Means sharing the same letter are not significantly different.

The Giza Red cultivar exhibited superior bulb quality under different chitosan concentrations, as indicated by higher dry matter, TSS, and pungency values compared with the Giza 20 cultivar. In addition, positive correlations were observed among dry matter, TSS, vitamin C, pungency, and bulb quality traits **(Table 10)**.

Table 10. Correlation coefficients among bulb dry matter, total soluble solids (TSS), and pungency of onion bulbs at harvest as influenced by the interaction between cultivars and foliar application of chitosan (mean of 2023/2024 and 2024/2025 seasons).

Treatments	TSS	Vitamin C	Pungency
Dry matter	0.95	0.99	0.86
TSS		0.93	0.90
Vitamin C			0.88
Pungency			

The superior vegetative growth and yield performance of Giza 20 may be attributed to its greater adaptability, higher photosynthetic efficiency, and better partitioning of assimilates toward bulb development, which collectively enhanced plant vigor and productivity. In contrast, Giza Red exhibited superiority in several bulb quality traits, potentially due to its genetic tendency for higher accumulation of pigments, dry matter, and bioactive compounds associated with bulb quality and storage characteristics.

4. Conclusions

The present study demonstrated that both onion cultivar and chitosan application significantly influenced growth, productivity, and bulb quality. The Giza 20 cultivar exhibited superior performance in terms of dry weight accumulation, photosynthetic pigments, and yield components, while Giza Red excelled in bulb quality traits, including K, TSS, dry matter, vitamin C, and pungency. Foliar application of chitosan markedly enhanced all measured parameters, with 1500 mg L^{-1} proving to be the most effective concentration. This improvement may be attributed to enhanced photosynthetic efficiency, nutrient uptake, and translocation of assimilates. The interaction results further confirmed that spraying Giza 20 with 1500 mg L^{-1} chitosan maximized growth and yield, whereas the same treatment applied to Giza Red optimized bulb quality. Therefore, chitosan application at 1500 mg L^{-1} can be recommended as an effective strategy to improve onion productivity and quality under similar growing conditions. Further studies are recommended to investigate the environmental implications of chitosan application under sandy soil conditions through the assessment of resource-use efficiency indicators such as Water Use Efficiency (WUE), Nitrogen Use Efficiency (NUE), and partial factor productivity of water and nutrients. Such evaluations would provide a more comprehensive understanding of the sustainability and eco-friendly potential of chitosan-based treatments in onion production systems.

Acknowledgments

The authors gratefully acknowledge the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia (Grant No. KFU261573), for supporting this research.

Authors' contributions

Conception and design, Amro I. A. Attia, Ahmed A.M. Mohsen, Hany G. Zyada, Hossam S. El-Beltagi, Ali Osman, Adel A. Rezk, and Enas A. Bardisi; analysis and interpretation of the data; Wael F. Shehata, Ali Osman, Tarek A. Shalaby, Ahmed M. Ismail; drafting of the paper, revising it critically for intellectual content, Amro I. A. Attia, Ahmed A.M. Mohsen, Hany G. Zyada, Hossam S. El-Beltagi, Ali Osman, Adel A. Rezk, and Enas A. Bardisi; All authors have read and approved the final manuscript.

Funding

This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia (Grant No. KFU261573).

Conflicts of interest

The authors declare no conflict of interest.

References

Abou-El-Hassan, S., Elmehrat, H. G., Ragab, A. A., Abo-Dahab, A., & Megiud, A. (2018). Growth, yield, bulb quality and storability of some onion cultivars response to compost, vermicompost and plant growth promoting rhizobacteria. *Middle East Journal of Agriculture Research, 7*(2), 292–306.

Amjad, M., Hussain, R., Mehmood, A., & Ahmad, I. (2024). Evaluation of chitosan application on growth, yield, and quality performance of onion cultivars 'Dayo'and 'Prema'in the winter season. *J Hortic Sci Technol*, 8–14.

Attia, S., Gad, N., & Abdel-Rahman, H. (2014). Effect of cobalt on growth, yield and production quality with mitotic and meiotic divisions in two onion cultivars. *Curr. Sci. Int, 3*, 122–131.

Battikha, A., Abdelaal, H., Abdalla, A., & Ibrahim, H. H. (2020). Nano chitosan-N fertilizer affecting the growth and productivity of onion plants under sandy soil conditions. *Journal of Environmental Studies and Researches, 10*(4), 1349–1359.

Boßelmann, F., Romano, P., Fabritius, H., Raabe, D., & Epple, M. (2007). The composition of the exoskeleton of two crustacea: The American lobster Homarus americanus and the edible crab Cancer pagurus. *Thermochimica Acta, 463*(1-2), 65–68.

Chibu, H. (2001). Effects of chitosan application on the growth of several crops. *CHITIN AND CHITOSAN-Chitin and chitosan in life science-*.

Demisie, R., & Tolessa, K. (2018). Growth and bulb yield of onion (Allium cepa L.) in response to plant density and variety in Jimma, South Western Ethiopia. *Advances in Crop Science and Technology, 6*(2), 357.

Duncan, D. B. (1955). Multiple range and multiple F tests. *biometrics, 11*(1), 1–42.

El Sayed, A. S. S., Enany, D. F. M., & Kadah, T. M. S. (2024). Economic and marketing efficiency of onion and garlic crops in Egypt (A case Study: Fayoum Governorate). *Journal of the Advances in Agricultural Researches, 29*(4), 808–823.

ElGhamry, A., Ghazi, D. A., & Kassem, A. (2024). Enhancing onion growth and yield quality via soil amendments and foliar nutrition under deficit irrigation. *Egyptian Journal of Soil Science, 64*(2), 523–542.

Farouk, S., Mosa, A., Taha, A., Ibrahim Heba, M., & El-Gahmery, A. (2011). Protective effect of humic acid and chitosan on radish (Raphanus sativus, L. var. sativus) plants subjected to cadmium stress. *Journal of Stress Physiology & Biochemistry, 7*(2), 99–116.

Fawzy, Z., El-Shal, Z., Li YunSheng, L. Y., Zhu OuYang, Z. O., & Sawan, O. M. (2012). Response of garlic (Allium sativum, L.) plants to foliar spraying of some bio-stimulants under sandy soil condition.

Gelaye, Y., Nakachew, K., & Ali, S. (2024). A review of the prospective effects of spacing and varieties on onion yield and yield components (Allium cepa L.) in Ethiopia. *The Scientific World Journal, 2024*(1), 2795747.

Geries, L., Elgizawy, E., Abo-Dahab, A., & Karam, S. (2012). Productivity and quality of two onion cultivars under organic, slow release and mineral fertilizers. *Journal of Plant Production, 3*(5), 835–846.

Geries, L., Omnia, H., & Marey, R. (2020). Soaking and foliar application with chitosan and nano chitosan to enhancing growth, productivity and quality of onion crop. *Plant Arch, 20*(2), 3584–3591.

Górnik, K., Grzesik, M., & Romanowska-Duda, B. (2008). The effect of chitosan on rooting of grapevine cuttings and on subsequent plant growth under drought and temperature stress. *Journal of Fruit and Ornamental Plant Research, 16*, 333–343.

Guan, Y.-j., Hu, J., Wang, X.-j., & Shao, C.-x. (2009). Seed priming with chitosan improves maize germination and seedling growth in relation to physiological changes under low temperature stress. *Journal of Zhejiang University Science B, 10*(6), 427–433.

Hadwiger, L., Klosterman, S., & Choi, J. (2002). The mode of action of chitosan and its oligomers in inducing plant promoters and developing disease resistance in plants. *Advances in chitin science, 5*, 452–457.

Jackson, M. (1973). Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India, 498*, 151–154.

JM, B. (1982). Total nitrogen. *Methods of soil analysis*, 595–624.

Kandil, A., Leilah, A., Mostafa, A. K., & Hassan, F. (2010). Growth, yield and storability of onion bulbs, as affected by irrigation treatments and cultivars referring to water consumption. *Journal of Plant Production, 1*(2), 193–204.

Kandil, A. A., Sharief, A. E., & Fathalla, F. H. (2013). Effect of organic and mineral fertilizers on vegetative growth, bulb yield and quality of onion cultivars.

Marey, R., & Morsy, M. (2010). Performance and genetic parameters for some Egyptian onion genotypes evaluated under Sohag conditions. *Journal of Plant Production, 1*(8), 1153–1163.

Mondal, M. M., Malek, M., Puteh, A., Ismail, M., Ashrafuzzaman, M., & Naher, L. (2012). Effect of foliar application of chitosan on growth and yield in okra. *Australian Journal of Crop Science, 6*(5), 918–921.

Mukarram, M., Ali, J., Dadkhah-Aghdash, H., Kurjak, D., Kačík, F., & Ďurkovič, J. (2023). Chitosan-induced biotic stress tolerance and crosstalk with phytohormones, antioxidants, and other signalling molecules. *Frontiers in Plant Science, 14*, 1217822.

Olsen, S., & Sommers, L. (1983). Phosphorus Page AL. *Methods of Soil Analysis*, 403–427.

Rai, S., Pokhrel, P., Udash, P., Chemjong, M., Bhattarai, N., Thuanthong, A., . . . Nirmal, N. (2025). Chitin and chitosan from shellfish waste and their applications in agriculture and biotechnology industries. *Critical Reviews in Biotechnology, 45*(7), 1508–1526.

Ratan, D., Gowda, R. V., & Pandey, H. (2017). Evaluation of different onion (Allium cepa L.) genotypes for yield and quality parameters in kharif season under Bengaluru conditions, India. *Intl. J. Curr. Microbiol. App. Sci, 6*(11), 2393–2398.

Ray, T., Gomasta, J., Hassan, J., Hossain, M. S., & Kayesh, E. (2023). Foliar application of chitosan and plant probiotic bacteria influencing the growth, productivity and bulb storage life of onion. *Australian Journal of Crop Science, 17*(10), 776–788.

Roshdy, A., & Khadr, A. (2023). Potential of chitosan in reducing GA3 doses and their effect on growth, yield, and bulb quality in “giza red” onion. *Iraqi Journal of Agricultural Sciences, 54*(2), 563–571.

Schwimmer, S., & Weston, W. (1961). Onion flavor and odor, enzymatic development of pyruvic acid in onion as a measure of pungency. *Journal of Agricultural and Food Chemistry, 9*(4), 301–304.

Shah, S. T., Muhammad Sajid, M. S., Riaz Alam, R. A., Abdur Rab, A. R., Abdul Mateen, A. M., Ibadullah Jan, I. J., . . . Wahid, F. I. (2012). Comparative study of onion cultivars at Mardan, Khyber Pakhtunkhwa-Pakistan.

Sharif, R., Mujtaba, M., Ur Rahman, M., Shalmani, A., Ahmad, H., Anwar, T., . . . Wang, X. (2018). The multifunctional role of chitosan in horticultural crops; a review. *Molecules, 23*(4), 872.

Shedeed, S. I., El-Sayed, S., & Bash, D. A. (2014). Effectiveness of bio-fertilizers with organic matter on the growth, yield and nutrient content of onion (Allium cepa L.) plants. *European International Journal of Science and Technology, 3*(9), 115–122.

Sheikha, S., & Al-Malki, F. (2011). Growth and chlorophyll responses of bean plants to the chitosan applications. *European Journal of Scientific Research, 50*(1), 124–134.

Soleymani, A., & Shahrajabian, M. H. (2012). Effects of different levels of nitrogen on yield and nitrate content of four spring onion genotypes. *International Journal of Agriculture and Crop Sciences, 4*(4), 179–182.

Sun, T., Yao, Q., Zhou, D., & Mao, F. (2008). Antioxidant activity of N-carboxymethyl chitosan oligosaccharides. *Bioorganic & medicinal chemistry letters, 18*(21), 5774–5776.

Svehla, G., Koltai, L., & Erdey, L. (1963). The use of 2, 6-dichlorophenol-indophenol as indicator in iodometric titrations with ascorbic acid. *Analytica Chimica Acta, 29*, 442–447.

Tantawy, I., Soltan, H., & Ezzat, A. S. (2021). Efficiency of foliar application by chitosan and royal jelly on growth, yield and quality of two garlic cultivars. *SVU-International Journal of Agricultural Sciences, 3*(4), 119–131.

von Wettstein, D. (1957). Chlorophyll-letale und der submikroskopische Formwechsel der Plastiden. *Experimental cell research, 12*(3), 427–506.

Yeshiwas, Y., Alemayehu, M., & Adgo, E. (2024). Influence of cultivar and plant density on the growth, bulb yield and quality traits of onion (Allium cepa L.). *Scientific Reports, 14*(1), 30729.