JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2023, 24(3), 341–356
https://doi.org/10.12911/22998993/158384
ISSN 2299–8993, License CC-BY 4.0

Received: 2022.11.28
Accepted: 2023.01.06
Published: 2023.01.15

Enhancement of Quinoa Grain Yield and Nutritional Quality by Potassium Fertilization Combined with Foliar Spraying of Seaweed Extract

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ABSTRACT

The current work was carried out during the two growing seasons of 2016/2017 and 2017/2018 at the Experimental Station of the Environmental Studies and Research Institute, University of Sadat City, Sadat City, Menofia Governorate, Egypt. It aimed to investigate the effect of applying potassium fertilizer at 90, 140 and 190 kg K_2O/ha combined with spraying applications of seaweed extract for four times in a 15-day interval starting at 40 days after sowing at rates of 0.0, 1.5 and 3.0 ml/L on the yield, mineral contents and nutritional quality of quinoa grains cv. CICA. A split-plot design was used in three replicates. Results reported that by increasing the application of potassium from 90 to 190 kg K_2O/ha, gradual increases in all studied parameters of quinoa grains occurred in the seasons of 2016–2017 and 2017–2018, except for class B grain, Mg and fiber contents. Potassium application at 190 kg K_2O/ha gave the highest significant values of all determined parameters in comparison with treatment of 90 kg K_2O/ha. In most cases, insignificant differences were detected between potassium fertilizer levels of 140 and 190 kg K_2O/ha. Spraying seaweed extract at 3.0 ml/L resulted in superiority of all studied characters except class B grain, Mg and fiber contents, followed by 1.5 ml/L treatment with insignificant differences between them in most cases. There were significant differences among spraying seaweed treatments on Ca, Fe, Mn, protein and fiber contents in both seasons, N, P and K during the first season, and grain yield/plant, total grain yield/ha and Zn content during the second season. The interaction between potassium fertilization levels and spraying applications of seaweed extract had significantly different effects on all studied characters during both seasons, except for Mg percentage. It is evident that the application of potassium fertilization at 140 or 190 kg K_2O/ha combined with the spraying of seaweed extract at 3.0 ml/L caused an apparent enhancement of the yield, mineral contents and nutritional quality of quinoa grains during the two experimental seasons.

Keywords: *Chenopodium quinoa*, grain yield, weight of 1000-grain, grain size, grain mineral contents, grain nutritional profiles.

INTRODUCTION

Climate change, water scarcity and the rapid growth population rate are the main constraints for the agricultural sector expansion in Egypt for producing more and safe food to meet the current and future food demand. Therefore, introducing new non-traditional crops that are promising, climate-proof, multi-purpose, and tolerant to various stressful conditions is the best strategy for overcoming such constraints (Eisa et al., 2017; Jaikishun et al., 2019). Quinoa (*Chenopodium quinoa* Willd.) belongs to the amaranth family. It is among the oldest pseudo-cereal crops worldwide, and it was sown as a staple food crop about 5000–7000 years ago for the Andes people of South America (Fuentes et al., 2012). Quinoa has been revived as a new, promising, non-traditional, climate-proof and multi-purpose crop. It has gained considerable worldwide attention as one of the most important crops destined for future global nutritional security for the world's increasing population, owing to its excellent nutritional values and exceptional tolerance to various harsh environmental conditions (FAO, 2013). Hence, quinoa was introduced to several countries around the world as a new crop. Recently, it has been cultivated outside the Andean regions in more than 120 countries around the world (Alandia et al., 2020). Several studies have been conducted on quinoa, aiming to integrate it into the Egyptian cropping pattern. Quinoa appeared to be an ideal, suitable, and promising new crop to be cultivated under newly reclaimed Egyptian soil conditions. However, it has not received adequate attention for its importance and unbelievable nutritional values, whereas public awareness of its value and potential does not yet exist (Shams, 2011; Eisa et al., 2017; Zohry, 2020; González et al., 2021). Quinoa has enormous potential; it is not only a gluten-free grain crop (Pereira et al., 2018; Villacrés et al., 2022), but it can also be used as a leafy greens crop (Abd El-Samad et al., 2018a; Pathan and Siddiqui, 2022), a fodder crop (Asher et al., 2020; Yilmaz et al., 2021) and in the food industry (Wang and Zhu 2016; Soliman et al., 2019).

Potassium (K^+) is an essential nutrient required by the plant for optimal growth, yield and quality, it is frequently referred to as a nutrient responsible for quality (Marschner, 1995). Potassium is one of the most abundant cations in plants, but it is not a constituent of any plant compounds, cellular organelles or structures, it constitutes 0.4–4.3% in the dry matter (Askegaard et al., 2004). It is associated directly with many important regulatory, biochemical and physiological processes supporting plant growth and development, including activating over 80 enzymes; regulating cellular osmotic water potential; regulating plant stomata and water use; photosynthesis; it also contributes to translocation of sugars and assimilates; formation of carbohydrates; protein metabolism and ameliorating plant tolerance to biotic and abiotic stressful conditions. In addition, it is needed for many other processes that sustain plant growth and reproduction (Kafkafi et al., 2002; Arif et al., 2008; Wang et al., 2013; Zörb et al., 2014).

Optimizing K requirements in order to improve plant growth yield and quality, particularly in newly reclaimed areas, is highly recommended (Zörb et al., 2014). Little information about the effects of potassium on quinoa grain yield has been published. In this context, the yield and quality of quinoa grains were significantly enhanced when potassium fertilizer was increased up to 120 kg/ha, but the application of 180 kg/ha caused a slight decrease (Salim et al., 2019). The same findings were reported by Akhtar et al. (2003) on peas, who reported that the best values of yield and quality traits were attained when potassium fertilizer was applied at 100 kg K_2O/ha, but above this rate further application of potassium was ineffective. Moreover, Petropoulos et al. (2022) showed that using 100 or 75% of the recommended potassium fertilizer dose recorded the best values for yield, quality parameters and chemical compositions of globe artichokes, without significant differences between them. However, Minh et al. (2022) showed that the optimum rate of potassium for quinoa grain yield was found to be 105 kg K_2O/ha which resulted in higher protein and fat contents but lower starch and fiber contents in grains. Furthermore, Kubar et al. (2019) found that application of potassium at 100 kg K_2O/ha markedly increased the yield attributes as well as N, P and K contents in wheat grains. According to Hefny (2021), increasing the potassium fertilizer application from 0 to 175 kg K_2O/ha, resulted in significant differences in the number of grains/spike, 1000-grain weight, and grain yield of durum wheat. Dar et al. (2021) revealed that application of potassium with 150 kg K_2O/ha to sunflower plants grown under drought stress improved yield and quality attributes. They also added that it has been found to be effective in alleviating the influence of drought stress on sunflower plants. In addition, improving the yield and chemical quality properties of dry beans could be achieved by applying potassium at 180 kg K_2O/ha (Abd El-Samad et al., 2018b). Seed yield and seed protein content of chickpea crops were improved by applying potash at 150 kg K_2O/ha, as reported by Asghar et al. (2007).

According to du Jardin (2015), plant growth stimulants are defined as any substance or microorganism applied to stimulate plant growth, yield, enhance nutrient availability and uptake, alleviate stress conditions and promote several biochemical and metabolic pathways in plant cells. It could be classified into two categories depending on their origin; natural (plant growth-promoting rhizobacteria, effective micro-organisms, chitosan and seaweed extracts) and synthetic (inorganic salts, plant growth regulators, antioxidants and phenolic compounds). Biologically, marine macroalgae could be classified into three sub-classes based on their dominant pigmentation; brown (*Phaeophyta*), red (*Rhodophyta*), and green algae (*Chlorophyta*) as mentioned by Khan et al. (2009).

Seaweed extracts are considered a natural and organic plant growth stimulant that promotes growth, yield and quality when applied in low quantities. Therefore, it has gained great importance and is widely used as an eco-friendly agronomic practice to achieve sustainable agricultural production for food safety and security (Craigie, 2011). Their stimulatory effect may be related to the existence of various useful bioactive substances, i.e., natural phytohormones, vitamins, polyphenols, polyamines, alginates, micro- and macronutrients and poly- and oligosaccharides (Khan et al., 2009; Stirk et al., 2014; Shukla et al., 2018). Such bioactive substances play a critical role in stimulating plant growth, delaying plant senescence, maximizing crop yield and quality, improving nutrient uptake and mitigating biotic and abiotic stresses. Therefore, the application of seaweed extract is widely used as a plant stimulator in the production of many crops (Battacharyya et al., 2015; Kocira et al., 2018; Bulgari et al., 2019; Mukherjee and Patel, 2020).

Quinoa plants positively responded to seaweed extract applied at 1 kg/ha, where it recorded superiority of 1000-grain weight and grain yield as compared to control treatment (Hasan et al., 2021). Moreover, Sriyuni et al. (2020) reported that using seaweed extract combined with amino acids is recommended to improve the growth and yield of rice. Rathore et al. (2009) reported that spraying application of seaweed extract at 15% significantly increased grain yield and nutrient uptake of soybean plants grown under rainfed conditions. Furthermore, Vasantharaja et al. (2019) revealed that spraying of seaweed extract at 3% enhanced the phytochemical contents, antioxidant activity and nutritional quality of cowpea seeds relative to control treatment. Ziaei and Pazoki (2022) revealed that spraying seaweed at 4 L/ha improved grain yield, protein content and TSS percentage, but did not affect the fatty acid content in grains of common bean cultivars. They also added that application of seaweed extract alleviates drought stress, which in turn improves crop yield. Petropoulos et al. (2022) indicated that spraying application of seaweed at 3 g/L showed a positive effect on yield, quality parameters and chemical compositions of globe artichoke plants.

The objective of this study was to evaluate the potential effects of applying mineral potassium fertilizer at 90, 140 and 190 kg K_2O/ha combined with spraying applications of seaweed extract at 0.0, 1.5 and 3.0 ml/L on the yield, mineral contents and nutritional quality of quinoa grains, cv. CICA.

MATERIALS AND METHODS

Plant material

The current study was carried out at the Experimental Station of the Environmental Studies and Research Institute, University of Sadat City, Sadat City, Menofia Governorate, Egypt (Latitude 30° 40’ 63” N; Longitude 30° 56’ 24” E; Elevation 36.2 m asl), during the growing seasons of 2016/2017 and 2017/2018 aiming to evaluate the potential effects of applying mineral potassium fertilizer at 90, 140 and 190 kg K_2O/ha combined with spraying applications of seaweed extract at 0.0, 1.5 and 3.0 ml/L on the yield, mineral contents and nutritional quality of quinoa grains cv. CICA. Grains of quinoa cultivar CICA were kindly obtained from the Faculty of Agriculture, Ain Shams University. The grains were surface sterilized before sowing to prevent any possible infection of seed-borne fungi. Sterilized quinoa grains were sown on October 10th in the two growing seasons of 2016/2017 and 2017/2018, in hills with a 15 cm distance among hills with a seeding rate of 5–8 seeds per hill at 2 cm depth on both sides of drip-irrigated ridges. Then, the germinated grains were thinned to 2 seedlings per hill after 3 weeks from the sowing date. The agricultural management practices for quinoa grain production were followed.

Experimental soil analysis

At the beginning of the experiment, three soil samples from the top layer (0 - 30 cm) were randomly collected from the experimental site. Then, the samples were subjected to classifying soil texture through particle size distribution analysis and determining some soil chemical characteristics according to the procedures described by Tandon (2000). The average of the particle size

Table 1. The particle size distribution and some chemical characteristics of the experimental soil

The particle size distribution and soil texture												
Sand (%)		Silt (%)			Clay (%)			Texture				
75.33		6.40			18.27			Sandy loam				
Chemical characteristics												
ECe (ds m^{-1})	pH	OM (%)	$CaCO_3$ (%)	Soluble cations (meq L^{-1})				Soluble anions (meq L^{-1})				
				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_4^{=}$	CO_3	HCO_3	Cl	
1.68	7.40	0.35	16.90	3.60	3.70	14.40	0.41	0.61	0.0	3.80	6.40	

distribution and some chemical characteristics of the soil samples are shown in Table 1.

Preparation of experimental site

The soil was prepared by plowing in two perpendicular directions and all plots of the experiment were supplied with compost at 20 tons/ha as organic manure, phosphorus fertilizer at 90 kg P_2O_5/ha as calcium superphosphate (15.5% P_2O_5) and agricultural sulfur at 180 kg/ha. Compost, phosphorus and sulfur were added once and mixed with the experimental soil before the construction of ridges. Nitrogen was used as ammonium sulfate (20.6% N) at 215 kg N/ha. The nitrogen units were divided into 8 portions, added after 10 days from the seeding date (first portion) and the remaining portions were subsequently applied at a rate of one portion every 7 days until grain setting. Nitrogen fertilizer was applied through injection in a drip irrigation system as a fertigation application.

Experimental design

The experiment was set up as a split-plot design in three replicates. Potassium application treatments (90, 140 and 190 kg K_2O/ha) were randomly arranged within the main plots, while the spraying application treatments of seaweed extract (0.0, 1.5 and 3.0 ml/L) were randomly organized within the sub-plots. The experimental sub-plot contained 5 ridges of drip-irrigated with 5 m length and 80 cm width, with a net area of 20 m^2. Furthermore, each experimental main or sub-plot was surrounded by a guard border of 1.0 m width from all sides to avoid overlapping among the treatments of potassium fertilization.

Experimental treatments

The calculated amounts of the three potassium levels, 90, 140 and 190 kg K_2O/ha, from a fully water soluble grade of potassium sulfate fertilizer (SoluPotasse® 0.0–50% K_2O and 18% S, Tessenderlo Kerley International Co., Brussels, Belgium; https://www.tessenderlokerley.com) were divided into 5 doses. The first dose, equal to 10% of the calculated potassium amounts, was added 40 days after sowing date through injection in a drip irrigation system as a fertigation application (potassium fertilizer solution was injected into the drip irrigation system before the end of irrigation time by 15–20 min). In turn, the remaining amount of calculated potassium was divided into 4 equal doses, each dose representing 22.5%, the second, third, fourth and fifth doses were added in a 10-day interval, after 50, 60, 70 and 80 days from sowing date, respectively.

Concerning foliar spraying treatments of seaweed extract, SEAGREEN®, a commercial seaweed extract was used. It is a mixture of two seaweeds, namely; *Ulva* sp and *Ascophyllum* sp. that contains 4% nitrogen, 6% phosphor, 6% potassium, 1.10% calcium, 0.95% magnesium, 0.078% iron, 0.18% zinc, 0.057% manganese, 0.17% copper and 15% potassium alginate (Agro Chemicals Lafortaleza Yesosy Escatolas, Ctra Pique, Spain, imported and distributed by El Masria Co. for Fertilizers and Trade, El-Noubaria region, Beheira Governorate, Egypt; http://www.masriafert.com). Foliar spraying of seaweed extract was applied four times in a 15-day interval during the growing period of quinoa plants, starting at 40 days after sowing date and then at 55, 70 and 85 days, respectively, at 1.5 and 3.0 ml/L plus tap water served as a control treatment (0.0 ml/L). The spraying solution of seaweed extract was freshly prepared upon application and a few drops of surfactant agent (Tween-20) were added to the spraying solution to ensure and improve spreading on the plant's foliage. Spraying solution was applied in an adequate amount to completely cover the quinoa plant foliage until it began to drip. All sprays were carried out at 9:30 a.m. using a hand pressure sprayer.

Data recorded

Harvesting of quinoa grain samples

At the harvesting stage, after 135 days from sowing date, a representative sample of 12 plants (group A plants), in addition to the plant samples from four square meters from the middle of each experimental sub-plot (group B plants), were randomly taken by cutting at ground level. Then, all plant samples were lifted and allowed to air dry for at least 7 days. Afterwards, each dried plant sample was threshed by hand to obtain the grains from the dried panicles per plant (group A plants) or from all plant samples per each experimental sub-plot (group B plants). Moreover, the grains were winnowed manually to clean and remove any foreign materials and broken or immature grains.

The cleaned grains of group A plants were used to determine parameters of grain yield/plant (g), total grain yield/hectare (kg) and 1000-grain weight (g). In contrast, the cleaned grains of group B plants were used to determine the grain size (mm) parameter. Thereafter, the cleaned grains of group B plants were dried in an electrical oven at 65°C for 48 hours. The dried grain samples were ground to a fine powder in a high-speed stainless steel mill and then subjected to various analyses of mineral contents and nutritional quality.

Grain yield

The grain yield/plant in each experimental sub-plot was determined by weighting the manually extracted and cleaned grains from each individual plant of group A plants using a 3-decimal digit electronic balance to obtain the average grain yield/plant in grams. Meanwhile, the total grain yield/hectare (kg) was calculated by multiplying the average grain yield per plant (g) by the average number of plants per hectare (a plant density of about 345 thousand plants per hectare).

Weight of 1000-grain

The weight of 1000-grain in grams was determined 3 times for each experimental sub-plot by counting 1000 grains from the previously manually extracted and cleaned grains from each individual plant in group A plants and then weighting them using a 3-decimal digit electronic balance to obtain the average weight of 1000-grains.

Percentage of grain size

The percentage of quinoa grain size was determined by passing 100 g of the previously manually extracted and cleaned grains from group B plants through sieves with different meshes for sizing quinoa grains by diameter into two classes; class A grain (large grain, equal to or larger than 2.0 mm) and class B grain (medium grain, less than 2.0 mm) using a RETSCH Vibratory Sieve Shaker device model AS-200 Basic. Grain sieving separation was performed 3 times for each experimental sub-plot and for 3 minutes of vibration in each time. The average weight of each grain size separated by sieves was recorded and expressed as a percentage.

Determination of grain mineral contents

From the fine powdered dried grain samples mentioned above, 0.2 g was used for wet digestion as described by Wolf (1982). On a dry weight basis, the grain mineral contents were determined in acid digested solutions. Nitrogen was assayed using the Kjeldahl method. In addition, phosphorus was analyzed using the modified colorimetric method using a spectrophotometrical method following the procedures of Cottenie et al. (1982). Potassium and calcium were determined using the flame photometer method. Furthermore, Mg, Fe, Zn and Mn were analyzed using atomic absorption spectroscopy according to the procedures of Chapman and Pratt (1982).

Nutritional quality of quinoa grains

Percentages of crude protein, crude fat and crude fiber

The crude protein percentage was calculated by multiplying the percentage of total nitrogen content in grain by a conversion factor of 6.25. In turn, the crude fiber percentage was determined in 1 g of powdered dried grain samples placed in an ANKOM fiber filter bag using the ANKOM Fiber Analyzer device model A-200. Moreover, crude fat percentage was determined in 5 g of powdered dried grain samples, placed in a VELP cellulose thimble, using a VELP solvent extractor device model SER 148/3 for a solvent extraction period of 120 minutes with petroleum ether (40–60°C boiling range).

Percentages of ash, dry matter and total carbohydrates

The ash and dry matter percentages were determined according to AOAC (2016). Ash percentage was carried out by burning 5 g of powdered dried grain samples in a muffle furnace at 525±25°C for 12 hrs. In order to determine the dry matter percentage, a constant weight of powdered dried grain samples was oven dried again, but at 105°C for 24 hrs. The differences between the weights before and after oven drying again were expressed as a dry matter percentage. In turn, the total carbohydrate content was calculated by difference using the equation described by Alonso-Miravalles and O'Mahony (2018) as follows:

$$\textit{Percentage of carbohydrates} = 100 - (\textit{Protein} + \textit{Fiber} + \textit{Fat} + \textit{Ash} + \textit{Moisture content})$$

Statistical analysis

The data were subjected to a statistical analysis of variance procedure of two-way ANOVA using SPSS computer software (SPSS Inc., released 2009, Ver. 18.0 for Windows, Chicago, Illinois, USA). Duncan's multiple range test (DMRT) was used to separate the significant differences among treatment means at the 5% level of significance according to the methods of Gomez and Gomez (1984).

RESULTS

Grain yield

Grain yield/plant and total grain yield/ha of quinoa plants positively responded to potassium application during both seasons. Increasing the potassium level from 90 to 190 kg K_2O/ha had significant increases in grain yield/plant and total grain yield/ha. With potassium application at 190 kg K_2O/ha, the highest values of grain yield/plant and total grain yield/hectare were obtained. In contrast, the lowest values were found with potassium application level of 90 kg K_2O/ha in the two seasons of 2016/2017 and 2017/2018. Furthermore, results indicated that insignificant differences were observed between potassium applications at 140 and 190 kg K_2O/ha on both characters during the two experimental seasons (Table 2).

Concerning exogenous application of seaweed extract, foliar applications of seaweed at 1.5 and 3.0 ml/L significantly increased grain yield/plant and total grain yield/ha of quinoa plants over

Table 2. The effect of different potassium fertilization levels as well as foliar spraying of seaweed extract (SW) at different rates and their interaction on quinoa grain yield attributes during the seasons of 2016/2017 and 2017/2018

Treatments		Grain yield/plant (g)		Total grain yield ($kg \cdot ha^{-1}$)		Weight of 1000-grains (g)	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
90 kg K_2O/ha		7.18 b	7.08 b	2477.10 b	2442.60 b	3.90 b	3.35 b
140 kg K_2O/ha		8.48 a	8.06 a	2925.60 a	2780.70 a	4.40 b	4.06 a
190 kg K_2O/ha		8.83 a	8.29 a	3046.35 a	2860.05 a	4.93 a	4.39 a
LSD at 5% level		0.839	0.428	269.74	177.61	0.514	0.421
Control		6.62 B	6.45 C	2283.90 B	2225.25 C	3.88 B	3.13 B
1.5 ml/L SW		8.75 A	8.33 B	3018.75 A	2873.85 B	4.52 A	4.21 A
3.0 ml/L SW		9.09 A	8.66 A	3136.05 A	2987.70 A	4.84 A	4.55 A
LSD at 5% level		0.408	0.260	133.66	97.03	0.615	0.791
90 kg K_2O/ha	Control	5.56 e	5.70 e	1918.20 e	1966.50 e	3.37 b	2.42 b
	1.5 ml/L SW	7.60 c	7.23 c	2622.00 c	2494.35 c	4.06 b	3.61 ab
	3.0 ml/L SW	8.37 b	8.30 b	2887.65 b	2863.50 b	4.28 ab	4.02 ab
140 kg K_2O/ha	Control	6.64 d	6.47 d	2290.80 d	2232.15 d	3.93 b	3.17 ab
	1.5 ml/L SW	9.15 a	8.68 ab	3156.75 a	2994.60 ab	4.52 ab	4.41 a
	3.0 ml/L SW	9.56 a	9.04 a	3298.20 a	3118.80 a	4.76 ab	4.86 a
190 kg K_2O/ha	Control	7.67 c	7.18 c	2646.15 c	2477.10 c	4.34 ab	3.80 ab
	1.5 ml/L SW	9.50 a	9.07 a	3277.50 a	3129.15 a	4.98 ab	4.62 a
	3.0 ml/L SW	9.33 a	8.63 b	3218.85 a	2977.35 b	5.47 a	4.76 a
LSD at 5% level		0.674	0.429	188.90	147.85	1.306	1.774

Note: Means followed by the same letter within each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

control treatment during both seasons (Table 2). There were significant differences among foliar spraying treatments of seaweed extract on grain yield/plant and total grain yield/ha in the second season. In turn, in the first season, insignificant differences were found between treatments of 1.5 and 3.0 ml/L on the aforementioned parameters.

Regarding the interaction between potassium fertilizer levels and spraying applications of seaweed, significant differences were detected on grain yield/plant and total grain yield/ha during both seasons. It was noticed that the quinoa plants fertilized with potassium at 140 kg K_2O/ha and applied seaweed extract at 3.0 ml/L as well as those fertilized with 190 kg K_2O/ha and foliar application seaweed at 1.5 ml/L, recorded the superiority of grain yield/plant and total grain yield/ha. In contrast, the quinoa plants treated with 90 kg K_2O/ha and sprayed application seaweed extract at 0.0 ml/L (control) recorded the lowest significant values of the above mentioned parameters during both seasons.

Weight of 1000-grain

The application of potassium fertilizer had a positive effect on the weight of 1000-grains, increasing the potassium application from 90 to 190 kg K_2O/ha, resulted in significant increases in 1000-grain weights during the first and second seasons, from 3.90 to 4.93 g and 3.35 to 4.39 g, respectively. During the first season, insignificant differences were detected between both potassium applications at 90 and 140 kg K_2O/ha. Moreover, insignificant differences were found between both potassium treatments of 140 and 190 kg K_2O/ha in the second season.

Increasing seaweed extract foliar application up to 3.0 ml/L caused an improvement in the weight of 1000-grain trait. Foliar application of seaweed at 3.0 ml/L led to the highest value of the weight of 1000-grains, followed insignificantly by 1.5 ml/L and significantly by control treatment (0.0 ml/L), which gave the lowest values for this trait during the two experimental seasons.

As for interaction between potassium fertilization and spraying applications of seaweed extract, an almost insignificant difference effect was found on the 1000-grain weight character among treatments during both seasons of the study. Generally, it could be pointed out that the highest value of 1000-grain weight was recorded when quinoa plants received potassium fertilizer at 140 or 190 kg K_2O/ha combined with sprayed seaweed at 3.0 ml/L. In contrast, when quinoa plants were fertilized with potassium at 90 kg K_2O/ha combined with sprayed of seaweed extract at 0.0 ml/L (control treatment), the lowest value was attained in both experimental seasons (Table 2).

Percentage of grain size

The data presented in Table 3 clearly showed that potassium fertilizer application led to a significant increment in the percentage of class A grain (large grains, equal to or larger than 2.0 mm) as well as a significant decrement in the percentage of class B grain (medium grains, less than 2.0 mm) during both seasons of the study. The potassium application at 190 kg K_2O/ha gave the highest significant values of class A grain (38.41 and 38.70%) as well as the lowest significant values of class B grain (61.59 and 61.30%). In contrast, the potassium application at 90 kg K_2O/ha gave the lowest significant values of class A grain (31.78 and 29.89%) and the highest significant values of class B grain (68.22 and 70.11%) in the first and second seasons, respectively. Significant differences were detected among potassium fertilizer treatments in the second season. Furthermore, in the first season, significant differences were noticed only between potassium treatments of 190 and 90 kg K_2O/ha.

The same trends were obtained with the effect of seaweed extract foliar spraying on the percentage of quinoa grain size during both experimental seasons. Foliar spraying of seaweed at 3.0 ml/L recorded the highest significant values of class A grain (39.38 and 39.56%) and the lowest significant values of class B grain (60.62 and 60.44%). In contrast, the control treatment (0.0 ml/L) gave the lowest significant values of class A grain (31.37 and 29.17%) and the highest significant values of class B grain (68.63 and 70.83%) in the first and second seasons, respectively. During both seasons of the study, there were no significant differences observed between foliar spraying seaweed at 1.5 and 3.0 ml/L.

Regarding the interaction effect between potassium fertilization and seaweed extract foliar spraying, there was a significant difference on the percentage of quinoa grain size during both seasons (Table 3). It is noticed that the quinoa plants that were supplied with potassium at 190 kg K_2O/ha combined with sprayed application of seaweed at 3.0 ml/L had the highest significant values of

Table 3. The effect of different potassium fertilization levels as well as foliar spraying with seaweed extract (SW) at different rates and their interaction on the percentage of quinoa grain size during the seasons of 2016/2017 and 2017/2018

Treatments		Grain size %			
		Class A ≥ 2 mm	Class B < 2 mm	Class A ≥ 2 mm	Class B < 2 mm
		1st season		2nd season	
90 kg K_2O/ha		31.78 b	68.22 a	29.89 c	70.11 a
140 kg K_2O/ha		35.28 ab	64.72 ab	35.05 b	64.95 b
190 kg K_2O/ha		38.41 a	61.59 b	38.70 a	61.30 c
LSD at 5% level		3.82	3.82	3.26	3.26
Control		31.37 B	68.63 A	29.17 B	70.83 A
1.5 ml/L SW		34.73 AB	65.27 AB	34.92 A	65.08 B
3.0 ml/L SW		39.38 A	60.62 B	39.56 A	60.44 B
LSD at 5% level		5.22	5.22	5.60	5.60
90 kg K_2O/ha	Control	28.33 c	71.67 a	24.67 d	75.33 a
	1.5 ml/L SW	31.67 bc	68.33 ab	30.33 c	69.67 b
	3.0 ml/L SW	35.33 b	64.67 bc	34.67 bc	65.33 bc
140 kg K_2O/ha	Control	31.62 bc	68.38 ab	30.16 c	69.84 b
	1.5 ml/L SW	33.76 b	66.24 b	35.67 bc	64.33 c
	3.0 ml/L SW	40.47 a	59.53 c	39.33 b	60.67 c
190 kg K_2O/ha	Control	34.15 b	65.85 b	32.67 c	67.33 bc
	1.5 ml/L SW	38.76 ab	61.24 c	38.76 b	61.24 c
	3.0 ml/L SW	42.33 a	57.67 c	44.67 a	55.33 d
LSD at 5% level		4.24	4.24	4.94	4.94

Note: Means followed by the same letter within each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

class A grain (42.33 and 44.67%) in both seasons, followed by those quinoa plants that received 140 kg K_2O/ha combined with sprayed application of seaweed at 3.0 ml/L but insignificantly during the first season (40.47%) and significantly during the second (39.33%). In the same regard, they recorded the lowest significant values of class B grain (57.67 and 55.33%) in both seasons, followed insignificantly in the first season (59.53%) and significantly in the second season (60.67%). Conversely, those quinoa plants fertilized with 90 kg K_2O/ha combined with 0.0 ml/L gave the lowest significant values of class A grain (28.33 and 24.67%) and the highest significant values of class B grain (71.67 and 75.33%) in both experimental seasons of 2016/2017 and 2017/2018.

Grain mineral contents

Application of potassium fertilizer up to 190 kg K_2O/ha led to significant increases in the percentages of all analyzed mineral contents in quinoa grains, i.e., N, P, K, Ca, Fe, Zn and Mn except the percentage of Mg during both experimental seasons (Tables 4 and 5). Although no significant difference was found among potassium fertilizer treatments on Mg content, the highest value of Mg content was recorded with 90 kg K_2O/ha while the lowest value was recorded with 190 kg K_2O/ha. Furthermore, significant differences were detected among potassium fertilizer treatments on the percentages of K, Ca, Fe and Mn. On the other hand, insignificant differences were detected between potassium treatments of 140 and 190 kg K_2O/ha on N, P and Zn during the two seasons.

Application of seaweed caused an enhancement in the percentages of all determined minerals in quinoa grains, except Mg in the two seasons. Foliar spraying of seaweed extract at 3.0 ml/L gave the highest significant percentages of N, P, K, Ca, Fe, Zn and Mn except Mg percentage in the two seasons, followed insignificantly by 1.5 ml/L treatment on Zn in the first season, and on N, P and K in the second season compared with control treatment. Moreover, significant differences were found among seaweed extract foliar spraying treatments on N, P, K, Ca, Fe and Mn percentages in the first season and on Ca, Fe, Zn and Mn percentages in the second season. In contrast, the highest and lowest values of Mg were recorded with seaweed extract at 0.0 and 3.0 ml/L treatments, respectively, during both experimental seasons.

Concerning the interaction between potassium fertilization and sprayed applications of seaweed, significant differences effect were detected on the percentages of all determined micro and macro-elements in quinoa grains except for Mg during both seasons of the study. It could be mentioned that when quinoa plants received potassium fertilizer levels of 140 or 190 kg K_2O/ha combined with sprayed seaweed at 3.0 ml/L, the highest percentage values of N, P, K, Ca, Fe, Zn and Mn as well as the lowest percentage value of Mg were recorded in quinoa grains. In contrast, the lowest percentage values of N, P, K, Ca, Fe, Zn and Mn and the highest percentage value of Mg in quinoa grains were attained when quinoa plants received 90 kg K_2O/ha combined with the control treatment (0.0 ml/L). These findings were completely true during both experimental seasons (Tables 4 and 5).

Nutritional quality of quinoa grains

Percentages of crude protein, crude fat and crude fiber

The application of 190 kg K_2O/ha treatment gave the highest significant values of crude protein and crude fat and the lowest significant value of crude fiber percentages. Over the two seasons, potassium treatment at 90 kg K_2O/ha led to the lowest significant values of crude protein and crude fat percentages as well as the highest significant value of crude fiber percentage. Insignificant differences were recorded between potassium applications of 140 and 190 kg K_2O/ha on crude protein, crude fat and crude fiber percentages during the two seasons, except for crude fiber in the second season, whereas insignificant differences were detected between treatments of 90 and 140 kg K_2O/ha (Table 6).

Increasing the application rate of seaweed extract from 0.0 to 3.0 ml/L caused a gradual increase in crude protein and crude fat as well as a gradual decrease in crude fiber percentages during both seasons. The quinoa plants sprayed with seaweed extract at 3.0 ml/L gave the highest significant values of crude protein (15.17 and 13.69%) and crude fat (4.37 and 4.39%), as well as the lowest value of crude fiber (4.173 and 3.262%). However, the highest significant value of crude fiber (5.238 and 4.760%) was found with foliar spraying treatment of 1.5 ml/L in the first and second seasons, respectively. Moreover, control treatment gave the lowest values of crude protein (12.05 and 10.68%) and crude fat (3.25 and 2.79%) in the first and second seasons, respectively. Significant differences were found among seaweed extract treatments on crude protein and crude fiber percentages, while no significant difference was noticed between both treatments of 3.0 and 1.5 ml/L on crude fat percentage during both seasons.

In terms of the interaction between potassium fertilizer treatments and spraying applications of seaweed extract, significant differences effect were detected on crude protein, crude fat and crude fiber percentages of quinoa grains in both experimental seasons. The quinoa plants that were fertilized with potassium at 190 kg K_2O/ha combined with seaweed sprayed application at 3.0 ml/L recorded the highest significant values of crude protein and crude fat as well as the lowest significant value of crude fiber percentages. However, the highest value of crude fiber percentage was reached when quinoa plants were fertilized with 90 kg K_2O/ha combined with seaweed extract at 1.5 ml/L. On the other hand, the quinoa plants that received potassium treatment of 90 kg K_2O/ha combined with control treatment (0.0 ml/L) had the lowest values of crude protein and crude fat percentages. These results are completely similar during the two seasons.

Percentages of ash, dry matter and total carbohydrates

There were significant increases in ash, dry matter and total carbohydrate percentages of quinoa grains with increasing potassium application levels from 90 to 190 kg K_2O/ha in the two seasons (Table 7). The highest significant values of ash, dry matter and total carbohydrate percentages were recorded by potassium treatment of 190 kg K_2O/ha, while potassium treatment of 90 kg K_2O/ha gave the lowest significant values during both seasons. In the same context, potassium treatments of 140 and 190 kg K_2O/ha showed no significant differences between them on ash, dry matter and total carbohydrate percentages in both experimental seasons, except for total carbohydrate percentage in the second season, whereas the three potassium fertilizer treatments showed significant differences among them.

Foliar application treatment of seaweed at 3.0 ml/L had a significant positive effect on ash, dry matter and total carbohydrate percentages in quinoa grains during both seasons (Table 7). Results pointed out that the highest significant values of ash, dry matter and carbohydrate percentages were

Table 4. The effect of different potassium fertilization levels as well as foliar spraying with seaweed extract (SW) at different rates and their interaction on the mineral contents in quinoa grains during the first season of 2016/2017

Treatments		%					ppm		
		N	P	K	Ca	Mg	Fe	Zn	Mn
90 kg K_2O/ha		2.012 b	0.328 b	1.661 c	0.930 c	0.321 a	92.76 c	12.76 b	58.00 c
140 kg K_2O/ha		2.303 a	0.419 a	2.125 b	1.111 b	0.294 a	124.40 b	13.86 a	63.25 b
190 kg K_2O/ha		2.373 a	0.421 a	2.291 a	1.248 a	0.276 a	132.10 a	14.49 a	66.58 a
LSD at 5% level		0.075	0.033	0.146	0.099	*N.S.	7.52	0.88	1.17
Control		1.928 C	0.297 C	1.695 C	0.835 C	0.342 A	87.32 C	12.46 B	57.37 C
1.5 ml/L SW		2.334 B	0.418 B	2.032 B	1.023 B	0.306 AB	117.15 B	14.26 A	62.07 B
3.0 ml/L SW		2.427 A	0.454 A	2.349 A	1.430 A	0.243 B	143.80 A	14.38 A	68.38 A
LSD at 5% level		0.079	0.035	0.154	0.104	0.082	7.89	0.92	1.22
90 kg K_2O/ha	Control	1.543 d	0.213 d	1.342 d	0.743 e	0.362 a	76.20 e	11.19 c	54.53 f
	1.5 ml/L SW	2.132 c	0.362 bc	1.564 cd	0.829 de	0.315 a	84.39 de	13.76 b	58.28 e
	3.0 ml/L SW	2.360 b	0.409 b	2.078 b	1.218 c	0.286 a	117.70 c	13.41 b	61.20 d
140 kg K_2O/ha	Control	2.099 c	0.336 c	1.740 c	0.821 de	0.350 a	90.08 d	12.65 bc	54.45 f
	1.5 ml/L SW	2.394 ab	0.441 ab	2.218 b	1.111 cd	0.309 a	127.66 c	14.32 ab	61.87 d
	3.0 ml/L SW	2.417 ab	0.481 a	2.416 ab	1.402 b	0.223 a	155.47 a	14.61 ab	73.42 a
190 kg K_2O/ha	Control	2.141 c	0.342 c	2.004 b	0.942 d	0.314 a	95.67 d	13.55 b	63.14 d
	1.5 ml/L SW	2.475 ab	0.450 ab	2.314 ab	1.130 c	0.294 a	142.40 b	14.78 ab	66.07 c
	3.0 ml/L SW	2.504 a	0.472 a	2.554 a	1.671 a	0.219 a	158.22 a	15.13 a	70.53 b
LSD at 5% level		0.130	0.057	0.253	0.171	N.S.	13.01	1.52	2.02

Note: *N.S. Non-significant.

Means followed by the same letter within each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

Table 5. The effect of different potassium fertilization levels as well as foliar spraying with seaweed extract (SW) at different rates and their interaction on the mineral contents in quinoa grains during the second season of 2017/2018

Treatments		%					ppm		
		N	P	K	Ca	Mg	Fe	Zn	Mn
90 kg K_2O/ha		1.818 b	0.247 b	1.617 c	1.042 c	0.306 a	86.16 c	11.81 b	55.73 c
140 kg K_2O/ha		2.023 a	0.372 a	1.899 b	1.247 b	0.293 a	118.21 b	13.74 a	60.93 b
190 kg K_2O/ha		2.111 a	0.378 a	2.143 a	1.591 a	0.270 a	140.86 a	14.07 a	64.45 a
LSD at 5% level		0.203	0.041	0.222	0.129	*N.S.	4.72	0.56	1.96
Control		1.709 B	0.269 B	1.661 B	0.979 C	0.314 A	75.07 C	11.61 C	53.74 C
1.5 ml/L SW		2.053 A	0.343 A	1.911 A	1.301 B	0.294 AB	123.18 B	13.21 B	61.06 B
3.0 ml/L SW		2.190 A	0.386 A	2.086 A	1.600 A	0.260 B	146.80 A	14.80 A	66.30 A
LSD at 5% level		0.244	0.044	0.231	0.135	0.042	4.48	0.59	2.15
90 kg K_2O/ha	Control	1.517 b	0.187 c	1.374 c	0.889 d	0.322 a	64.73 f	10.74 e	51.72 e
	1.5 ml/L SW	1.918 b	0.217 c	1.648 bc	1.020 cd	0.306 a	89.34 e	11.45 de	55.41 d
	3.0 ml/L SW	2.018 ab	0.337 b	1.829 b	1.217 c	0.289 a	105.77 d	13.24 cd	60.06 c
140 kg K_2O/ha	Control	1.791 b	0.302 b	1.598 bc	0.940 d	0.315 a	69.87 f	12.27 d	54.54 de
	1.5 ml/L SW	2.079 ab	0.403 ab	1.983 ab	1.231 c	0.295 a	136.28 c	13.97 c	61.68 c
	3.0 ml/L SW	2.200 ab	0.412 a	2.115 ab	1.571 b	0.268 a	148.47 b	14.97 b	66.57 b
190 kg K_2O/ha	Control	1.819 b	0.317 b	2.011 ab	1.107 cd	0.305 a	90.60 e	11.81 d	54.95 de
	1.5 ml/L SW	2.162 ab	0.408 ab	2.103 ab	1.653 b	0.281 a	145.80 b	14.20 bc	66.11 b
	3.0 ml/L SW	2.351 a	0.410 a	2.314 a	2.013 a	0.224 a	186.17 a	16.19 a	72.28 a
LSD at 5% level		0.403	0.072	0.384	0.223	N.S.	7.40	0.97	3.39

Note: *N.S. Non-significant.

Means followed by the same letter within each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

Table 6. The effect of different potassium fertilization levels as well as foliar spraying with seaweed extract (SW) at different rates and their interaction on the nutritional quality traits in quinoa grains during the seasons of 2016/2017 and 2017/2018

Treatments		Crude protein (%)		Crude fat (%)		Crude fiber (%)	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
90 kg K_2O/ha		12.58 b	11.36 b	3.36 b	3.28 b	4.929 a	4.339 a
140 kg K_2O/ha		14.39 a	12.64 a	4.25 a	3.84 a	4.687 ab	4.143 a
190 kg K_2O/ha		14.83 a	13.19 a	4.36 a	4.01 a	4.454 b	3.624 b
LSD at 5% level		0.470	1.255	0.340	0.335	0.296	0.339
Control		12.05 C	10.68 C	3.25 B	2.79 B	4.664 B	4.085 B
1.5 ml/L SW		14.59 B	12.83 B	4.34 A	4.11 A	5.238 A	4.760 A
3.0 ml/L SW		15.17 A	13.69 A	4.37 A	4.39 A	4.173 C	3.262 C
LSD at 5% level		0.494	0.526	0.365	0.351	0.311	0.356
90 kg K_2O/ha	Control	9.64 d	9.48 d	2.94 d	2.53 d	5.014 ab	4.345 b
	1.5 ml/L SW	13.33 c	11.99 bc	3.45 cd	3.37 bc	5.357 a	5.100 a
	3.0 ml/L SW	14.75 b	12.61 bc	3.69 c	3.93 b	4.415 bc	3.573 c
140 kg K_2O/ha	Control	13.12 c	11.19 c	3.37 cd	2.67 cd	4.742 b	4.153 bc
	1.5 ml/L SW	14.96 ab	12.99 b	5.09 a	4.18 ab	5.123 ab	4.937 a
	3.0 ml/L SW	15.11 ab	13.75 ab	4.29 b	4.66 a	4.197 c	3.340 cd
190 kg K_2O/ha	Control	13.38 c	11.37 c	3.45 cd	3.18 c	4.237 bc	3.756 c
	1.5 ml/L SW	15.47 ab	13.51 ab	4.49 b	4.27 ab	5.233 ab	4.243 bc
	3.0 ml/L SW	15.65 a	14.69 a	5.14 a	4.59 a	3.907 c	2.873 d
LSD at 5% level		0.815	1.52	0.588	0.580	0.513	0.588

Note: Means followed by the same letter within each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

Table 7. The effect of different potassium fertilization levels as well as foliar spraying with seaweed extract (SW) at different rates and their interaction on the nutritional quality traits in quinoa grains during the seasons of 2016/2017 and 2017/2018

Treatments		Ash (%)		Dry matter (%)		Total carbohydrates (%)	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
90 kg K_2O/ha		4.766 b	4.513 b	90.67 b	89.10 b	63.49 b	64.63 c
140 kg K_2O/ha		5.131 a	5.309 a	92.92 a	92.33 a	64.50 a	66.04 b
190 kg K_2O/ha		5.406 a	5.532 a	93.26 a	93.22 a	65.36 a	67.62 a
LSD at 5% level		0.352	0.302	1.61	2.09	0.98	1.19
Control		4.586 B	4.676 B	90.65 B	89.80 B	62.62 B	65.03 B
1.5 ml/L SW		5.169 A	5.164 A	92.30 A	91.66 A	64.93 A	66.35 A
3.0 ml/L SW		5.549 A	5.513 A	93.90 A	93.19 A	65.81 A	66.92 A
LSD at 5% level		0.401	0.417	1.63	1.82	1.86	1.31
90 kg K_2O/ha	Control	4.112 c	4.077 c	88.69 b	86.81 c	61.81 b	63.56 b
	1.5 ml/L SW	5.023 b	4.448 c	90.13 b	89.47 bc	63.50 b	65.09 b
	3.0 ml/L SW	5.163 b	5.014 b	93.18 ab	91.02 b	65.16 ab	65.25 b
140 kg K_2O/ha	Control	4.673 bc	4.847 bc	91.19 b	90.43 b	62.97 b	64.98 b
	1.5 ml/L SW	5.270 b	5.368 ab	93.28 ab	92.56 ab	65.25 ab	66.38 ab
	3.0 ml/L SW	5.450 ab	5.711 a	94.30 a	94.00 ab	65.29 ab	66.75 ab
190 kg K_2O/ha	Control	4.973 b	5.104 b	92.08 ab	92.16 ab	63.07 b	66.54 ab
	1.5 ml/L SW	5.213 b	5.677 a	93.48 ab	92.95 ab	66.04 ab	67.57 ab
	3.0 ml/L SW	6.033 a	5.815 a	94.23 a	94.54 a	66.98 a	68.75 a
LSD at 5% level		0.662	0.524	2.78	3.36	3.08	3.27

Note: Means followed by the same letter within each column are not significantly different at $P \leq 0.05$ according to Duncan's multiple range test.

recorded with foliar application of seaweed at 3.0 ml/L, followed in descending order, insignificantly by seaweed extract treatment at 1.5 ml/L, and significantly at 0.0 ml/L in both experimental seasons.

The interaction between potassium fertilizer levels and spraying applications of seaweed extract detected significant differences on the percentages of ash, dry matter and total carbohydrates in quinoa grains during both seasons. It is evident from the obtained results that the experimental treatments (potassium fertilizer combined with spraying of seaweed extract) caused an enhancement in the nutritional quality of quinoa grains expressed as ash, dry matter and total carbohydrate percentages relative to the control treatment during the two seasons.

It is worth mentioning that the highest values of ash, dry matter and total carbohydrate percentages in quinoa grains could be attained by fertilizing quinoa plants with potassium at 140 or 190 kg K_2O/ha, combined with foliar application of seaweed at 3.0 ml/L. However, no significant differences were detected between the two experimental treatments. Nevertheless, the lowest values of the aforementioned traits were attained by fertilizing quinoa plants with 90 kg K_2O/ha combined with foliar application of seaweed at 0.0 ml/L. Similar results were obtained during the two seasons of 2016/2017 and 2017/2018.

DISCUSSION

Increasing potassium fertilizer up to 190 kg K_2O/ha resulted in significant increases in grain yield/plant, total grain yield/ha, weight of 1000-grains and class A grain percentage, but decreased class B grain percentage. In most cases, insignificant differences were detected between the two potassium treatments of 140 and 190 kg K_2O/ha during the two seasons (Tables 2 and 3). The achieved results are in line with Asghar et al. (2007); Shaheen et al. (2011); Abd El-Samad et al. (2018b); Kubar et al. (2019); Hefny (2021); Minh et al. (2022). They reported that potassium had significant positive effects on yield and quality. Increasing the potassium application level significantly led to the best values of yield and yield attributes. Furthermore, the application of excess potassium fertilizer beyond the optimum level was found to be ineffective (Akhtar et al., 2003), caused a slight decrease (Salim et al., 2019) or appeared to have no significant differences (Darwish et al., 2022; Petropoulos et al., 2022).

The superiority of grain yield and grain yield attribute recorded with increasing potassium application levels could be ascribed to that potassium is frequently referred to as a nutrient responsible for quality and it has an essential role in improving the weight and size of grains, which are important traits for market demand (Marschner, 1995). Furthermore, potassium is associated with many important metabolic processes, including the activation of over 80 enzymes; photosynthesis; formation of carbohydrates (Arif et al., 2008; Zörb et al., 2014) and the translocation of sugars, photo-assimilates and nutrients from source tissues (leaves and metabolic points) to sink tissues (reproductive tissue and growing points), as reported by Pettigrew (2008), which ultimately led to improving plant growth and yield as well.

Exogenous application of seaweed at 3.0 ml/L on quinoa plants significantly increased grain yield/plant, total grain yield/ha, weight of 1000-grains and class A grain percentage, while decreasing class B grain percentage in comparison to control treatment. Spraying seaweed at 1.5 and 3.0 ml/L recorded insignificant differences between both of them on the above-mentioned traits during both seasons of the study, except for grain yield/plant and total grain yield/ha in the second season. The attained results are in agreement with Rathore et al. (2009); Mahmoud et al. (2019); Sriyuni et al. (2020); Hasan et al. (2021); Ziaei and Pazoki (2022). They reported that spraying seaweed extract led to an increase in yield and yield attributes in comparison with un-treated plants.

The stimulatory effects of foliar sprayed seaweed extract on yield and yield attributes may be related to the existence of various useful bioactive substances. Such bioactive substances resulted in stimulating plant growth, delaying plant senescence and maximizing crop yield and quality (Stirk et al., 2014; Battacharyya et al., 2015; Kocira et al., 2018; Mukherjee and Patel, 2020). In addition, the application of seaweed extract resulted in a significant increase in leaf photosynthetic pigments, as well as a reduction in chlorophyll degradation rate (loss of greenness), as a result, the photosynthesis ability was prolonged (Battacharyya et al., 2015; Kulkarni et al., 2019) which in turn improves crop yield and quality.

Application of potassium fertilizer up to 190 kg K_2O/ha increased the values of N, P, K, Ca, Fe, Zn and Mn percentages within quinoa grains, except for Mg. Moreover, significant differences were detected among potassium fertilizer treatments on the K, Ca, Fe and Mn contents. In turn, potassium applications of 140 and 190 kg K_2O/ha recorded no significant differences between them on N, P and Zn in both experimental seasons (Tables 4 and 5). The concluded results are in agreement with Abd El-Samad et al. (2018b); Kubar et al. (2019); Dar et al. (2021); Petropoulos et al. (2022). They reported that potassium fertilization significantly enhanced the mineral content. In addition, a reduction in Mg absorption was observed with the application of higher levels of potassium, demonstrating the unilateral antagonistic interaction (Marschner, 1995). In the same regard, potassium is essential for increasing plant root growth and enhancing the uptake of N, P, Fe and Mn by the plants (Fageria and Oliveira, 2014).

The promotion effect of potassium on the mineral contents in quinoa grains might be attributed to that potassium is involved in many physiological, biochemical, regulatory and metabolic pathways in the plant (Kafkafi et al., 2002; Zörb et al., 2014). Furthermore, it enhanced root growth and improved absorption of nutrients and ionic balance, resulting in increased nutrient contents (Marschner, 1995; Kubar et al., 2019). In addition, potassium markedly maintains the turgor pressure of cells, regulates the cellular osmotic water potential, and assists in the opening and closing of stomata. Therefore, the ability of water and nutrient uptake and translocation within the plant via xylem, as well as water use efficiency (WUE), were augmented even under normal or stressful conditions (Zörb et al., 2014; Turcios et al., 2021). Moreover, Wang et al. (2013) noticed an excess in potassium uptake and accumulation by the plant during the optimum growth conditions and when potassium presented sufficiently in the soil as a "luxury consumption phenomenon". This might be explained as a "plant's defense strategy" for better dealing with sudden exposure to stressful conditions.

The use of seaweed extract caused an enhancement in all measured minerals in quinoa grains except for Mg percentage. In most cases, significant differences were observed among seaweed extract treatments on mineral contents in quinoa grains during both seasons. The positive effects of spraying seaweed extract on the mineral contents are reported by Rathore et al. (2009); Mahmoud et al. (2019); Petropoulos et al. (2022), who supported the findings obtained in this paper. In addition, they reported that the mineral contents in seaweed sprayed plants were significantly higher than those of non-sprayed plants.

The obtained results could be explained by the presence of useful bioactive substances, which led to an increase in the building of better roots, particularly lateral roots and fibrous rootlets that are responsible for water and nutrient absorption (Rathore et al., 2009; Stirk et al., 2014). In addition, seaweed is a natural source of nutrients (Battacharyya et al., 2015).

It is evident that the potassium fertilization treatment up to 190 kg K_2O/ha caused an improvement in the nutritional quality of quinoa grains expressed as protein, fat, ash, dry matter and total carbohydrate percentages relative to 90 kg K_2O/ha treatment except for fiber percentage during both seasons (Tables 6 and 7). These results agreed with those previously reported by Asghar et al. (2007); Abd El-Samad et al. (2018b); Dar et al. (2021); Petropoulos et al. (2022). They illustrated that potassium not only affected yield but also improved the nutritional profile and chemical composition, which in turn reflected on the quality. In addition, potassium led to an increase in yield and protein and fat contents but decreased fiber and starch contents in quinoa grains (Minh et al., 2022).

The obtained results are most likely due to potassium being referred to as a nutrient responsible for quality (Marschner, 1995). Moreover, it contributes to many important biochemical and metabolic pathways in the plant, including activating more than 80 enzymes, the formation of carbohydrates, protein metabolism and regulating the photosynthesis process (Arif et al., 2008; Zörb et al., 2014), which ultimately leads to improving grain nutritional quality. Furthermore, the apparent increment in yield and nutritional quality of quinoa grains with application of the highest fertilizer rate of potassium could be attributed to the vital role of potassium in delaying plant senescence (Darwish et al., 2022) as well as extending the duration of translocation of carbohydrates, photo-assimilates, metabolites and nutrients from the source to the sink (Pettigrew, 2008; Darwish et al., 2022).

The superior values of protein, fat, ash, dry matter and total carbohydrate in quinoa grains were recorded with seaweed application at 3.0 ml/L except for fiber percentage during both seasons. The achieved results agree with Kocira et al. (2018); Mahmoud et al. (2019); Vasantharaja et al. (2019); Petropoulos et al. (2022). They mentioned that spraying seaweed extract improved the nutritional quality and chemical composition of crops. In addition, enhanced protein and TSS contents but no effects on fatty acid profiles in seeds of common bean cultivars were observed (Ziaei and Pazoki, 2022).

The positive effect of spraying seaweed extract on grain nutritional quality traits could be explained by the presence of various bioactive substances, as well as secondary metabolites. Such substances maintained a high chlorophyll content in plant leaves by reducing the chlorophyll degradation rate (Battacharyya et al., 2015), which ultimately preserved the capacity and efficiency of production of photo-assimilates for a longer period and then reflected on the grains nutritional quality (Bulgari et al., 2015; Mahmoud et al., 2019; Mukherjee and Patel, 2020).

CONCLUSIONS

On the basis of the results of this study, it is possible to conclude that the maximum yield, mineral contents, as well as nutritional quality of quinoa grains cv. CICA grown under sandy soil conditions could be achieved by applying experimental treatments of potassium fertilizer levels of 140 or 190 kg K_2O/ha combined with spraying seaweed at 3.0 ml/L for four times during the growth period of quinoa plants in a 15-day interval starting after 40 days from the sowing date. Such experimental treatments showed no significant differences between them on most of the determined parameters.

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