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Original article

Can deficit irrigations be an optimum solution for increasing water productivity under arid conditions? A case study on wheat plants

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ABSTRACT

Water scarcity is of growing concern in many countries around the world, especially within the arid and semi-arid zones. Accordingly, rationalizing irrigation water has become an obligation to achieve the sustainable developmental goals of these countries. This may take place via using deficit irrigation which is long thought to be an effective strategy to save and improve water productivity. The current study is a trial to evaluate the pros and cons of using 50 and 75 % of the irrigation requirements (IR) of wheat (deficit irrigations) versus 100 %IR, while precisely charting changes in wheat growth parameters, antioxidant enzymes in plant shoots and the overall nutritional status of plants (NPK contents). Accordingly, a field experiment was conducted for two successive seasons, followed a split-plot design in which deficit irrigations (two irrigations to achieve 50 % of the irrigations requirements (IR), three irrigations to attain 75 % IR, and four irrigations to fulfill 100 % IR) were placed in main plots while four different studied wheat cultivars were in subplots. Results obtained herein indicate that deficit irrigations led to significant reductions in growth parameters and productivity of all wheat cultivars, especially when using 50 % IR. It also decreased NPK contents within plant shoots while elevated their contents of proline, peroxidase, and catalase enzymes. On the other hand, this type of irrigation decreased virtual water content (VWC, the amount of water used in production on ton of wheat grains). Stress tolerance index (STI), and financial revenues per unit area were also assessed. The obtained values of grain productivity, STI, VWC and financial revenues were weighted via PCA analyses, and then introduced in a novel model to estimate the efficiency of deficit irrigations (ODEI) whose results specified that the overall efficiency decreased as follows: 50 %IR < 75 %IR < 100 %IR. In conclusion, deficit irrigation is not deemed appropriate for rationalizing irrigation water while growing wheat on arid soils.

1. Introduction

Water scarcity is a worldwide growing concern (Saud et al., 2014 and 2020; Ahmed et al., 2022) threating food insecurity (Fahad et al., 2017; Ouda and Zohry, 2020), especially in arid and semi-arid zones (Abdelaal and Thilmany, 2019). Egypt is one of the arid countries that suffer from water scarcity (Wahba et al., 2018; Hussein et al., 2022). Its agricultural sector uses up to 80–85 % of the available water resources (Mahmoud and El-Bably, 2019). Only 8 % of its National Water Footprint (NWF), which is defined **as** total fresh water amount used in making products and/or services (Zaimes and Khanna, 2015), is saved through imports, embodied mainly in wheat (Wahba, et al., 2018). This amount of savings is not enough to achieve sustainable economic

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development (Molden, 2020). In parallel, rationalizing the usage of irrigation water is a must to increase the water budget, probably via using efficient irrigation systems (Eissa et al., 2018) and/or following deficit irrigations (Ouda and Noreldin, 2020).

The concepts and strategies of "virtual water" trade, which refers to the volume of water embodied in food crops (Shtull-Trauring and Bernstein, 2018; Liu et al., 2019), should be considered precisely in any developmental plans to improve the efficiency of water use (Sun et al., 2021). Wheat was the first grown crop (Abdelmageed et al., 2019) and a strategic crop in Egypt (Kherallah et al., 2003). It is the main ingredient in the Egyptian diet (Veninga and Ihle, 2018). In spite of that, its production accounts for only 62 % of the total consumption (Ouda and Zohry, 2016); therefore, the Egyptian government imports wheat from other countries to ensure food security (Veninga and Ihle, 2018). Unfortunately, Egypt has become the largest importer of wheat worldwide (Alwang et al., 2018; Asseng et al., 2018). Thus, the current study is a trial to highlight the implications of rationalizing water through deficit irrigations on the growth and productivity of different wheat cultivars under the arid soil conditions of Egypt. This approach (deficit irrigations) has been previously introduced as one of the most successful strategies to rationalize irrigation water and increase water productivity (Alghawry et al., 2021). It may also increase nutrient uptake by plants; improve physiological traits, e.g., photosynthesis (Chai et al., 2015), increases plant productivity (Hammad et al., 2020) and the net financial return (Garg and Dadhich, 2014; Himanshu et al., 2021). Nevertheless, many researches highlighted the negative impacts of water stress conditions on decreasing the metabolic processes in plants (Amjad et al., 2021) and leaf turgor pressure (Hammad et al., 2018). This considerably minimizes crop productivity (Hammad et al., 2017; Zia et al., 2017; Mubeen et al., 2020; Nagim et al., 2021; Nazim et al., 2021).

Accordingly, the current study precisely charted the changes in wheat growth parameters, osmoprotectants (proline), antioxidant enzymes in plant shoots and the overall nutritional status of plants (NPK contents) subjected to deficit irrigations i.e. 50 and 75 % of the irrigation requirements (IR). Furthermore, grain productivity, stress tolerance index, virtual water content (the amount of water used in production on ton of wheat grains), and net profit per unit area were assessed. The obtained values were weighted via PCA analyses, and then introduced in a novel model to estimate the overall efficiency of deficit irrigations (ODEI). This aim is not so far attained. Specifically, we anticipate that deficit irrigations (75 % and 50 % IR) might have negative consequences on wheat growth and productivity (hypothesis 1); yet the overall efficiency of deficit irrigations could be higher than the corresponding ones attained for full irrigation environments in arid countries (hypothesis 2). We believe that the results obtained herein could effectively improve our knowledge about the pros and cons of using deficit irrigations for wheat production in arid soils while ensuring food security.

2. Materials and methods

2.1. Materials of study

2.1.1. Experimental site and soil sampling

A field study was conducted at the Agricultural Research and Experimental Center (AREC), Faculty of Agriculture, at Moshtohor, Benha University, Kalubia Governorate, Egypt (30° 21′ 07″ N and 31° 13′ 34″ E) for two successive seasons to investigate the implications of using deficit irrigations on wheat growth and productivity. The preceding crop in this location for both seasons was maize. This area is considered within the semi-arid region at 20 m above sea level. The average temperature in summer is 27.4 °C while in winter this temperature becomes 12.9 °C (Bassouny and Abbas, 2019). The climatological data of the experimental location during the growing seasons (winter 2018/2019 and winter 2019/2020) were obtained from the Central Laboratory for Agri-cultural Climate (CLAC), Agricultural Research Center (ARC), Ministry of Agriculture, Egypt as shown in Table S1.

Prior to wheat cultivation, surface soil samples (0–30 cm depth) were collected from the investigation location, air dried, crushed, and sieved via 2-mm sieve then analyzed for their chemical characteristics and particle size distribution as outlined by Sparks et al. (1996) and Klute (1986). The obtained results are presented in Table S2.

2.1.2. Winter wheat cultivars

Four winter wheat cultivars i.e. three bread cultivars named Giza-168, Gemaiza-11, Misr-1, and a durum cultivar called Beni sweif-5 were selected for the current investigation (Table S3). These cultivars were obtained from the Wheat Research Department, Field Crops Research Institute, Agriculture Research Center (ARC), Ministry of Agriculture, Egypt.

2.2. Experimental design and the field study

Under arid conditions, four irrigations following the sowing one are guaranteed to satisfy water needs for wheat production (Taha et al., 2017; Zhou et al., 2018), with a total amount of 2400 m^3 ha^{-1}. In this study, deficit irrigations using 2 (1190 m^3 ha^{-1}) and 3 (1786 m^3 ha^{-1}) irrigations were tested for their efficiencies on wheat growth and productivity versus the reference treatment (2380 m^3 ha^{-1} using 4 irrigations). This investigation followed a split-plot design in which deficit irrigation treatments were found in whole plots while different wheat cultivars were placed in sub-plots. The area of each experimental unit was 10.5 m^2 (3 × 3.5 m). Seeds of different wheat cultivars were sown on the 24th November (winter 2018/19), and on the 27th November (2019/20) at a rate of 145 kg ha^{-1} and all plots received the recommended rates of NPK fertilizers according to the recommendations of the Egyptian Ministry of Agriculture i.e. 180 kg N ha^{-1} as Urea (46 % N), 75 kg P ha^{-1} as mono superphosphate (15 % P_2O_5), and 120 kg K ha^{-1} as potassium sulfate (48 % K_2O).

Water discharge was determined by triangular weirs (V notch). The height of flowing water was fixed at 30 cm water discharge was counted according to the equation of Hansen et al. (1980), as follows:

$$Q = 0.0138xh^{2.5}x3.6 \tag{1}$$

where:

(1) Q = Water discharge, m^3/h;
(2) 0.0138 and 3.6 are constant values, where 3.6 was added for obtaining Q (m^3/h);
(3) h = Water height or pressure head (cm).

The traditional-irrigation treatment was set as a control (100 % IR) in which these irrigations took place at the following wheat growth stages: (1) upstanding, (2) flowering, (3) booting stages, and (4) grain filling corresponding to 45, 90, 120, and 135 days after planting, respectively. Two deficit irrigations were also considered i.e. two irrigations at upstanding and booting stages to satisfy 50 % IR and three irrigations at upstanding, flowering, and booting stages to satisfy 75 % IR.

2.3. Plant growth parameters and yield components

At 80 days of planting, samples of plant shoots were collected, washed and dried at 70 °C for 48 h. These samples were ground and sieved. Plant portions (equivalent to 0.2 g dry weight samples) were taken from each treatment then digested with hydrogen peroxide and concentrated sulfuric acid (H_2SO_4) as outlined by Parkinson and Allen (1975). NPK were determined in plant digest according to the standard methods described by Sparks et al. (1996) as follows: N by micro-Kjeldhal, P by spectrophotometer (Jenway Model- 6315, England) after being reduced following the molybdate -ascorbic acid method while K by flame photometer (Sherwood Model- 410, England). Other fresh leaf samples were collected from each treatment, ground in a mortar in presence of sodium phosphate (0.1 M, pH = 7.1), then filtered through four layers of cheesecloth, and centrifuged at 3000 rpm (Tuzun et al., 1989; Mohamed et al., 2019; Abdelhafez et al., 2021). Afterward, activities of catalase (Sadasivam and Manickam, 1996) and peroxidase (Allam and Hollis, 1972) were determined using a spectrophotometer at 240 and 425 nm (Jenway Model- 6315, England), respectively. In case of Proline, its content was determined according the method of Bates et al. (1973), and then measured using a spectrophotometer at 520 nm.

At the physiological maturity stage (160 days after planting), wheat plants were harvested. Their straw, gain and biological (grain yield + straw yield) yields were determined per plot. Ten plants were selected randomly from the inner square meter of each experimental unit to assess the following measurements: (1) plant height: measured from the soil surface up to the spike top (excluding the awn), (2) number of tillers/m^2, (3) spike length, (4) number of spikelets/spike, (5) weight of spike (g) and (6) 1000-grain weight (g).

2.4. Statistical analysis

The obtained data of each growing season were individually analyzed using SPSS (ver. 18) statistical software through analysis of variance (2 way-ANOVA) and Dunkan's tests to compare among means. All graphs were plotted using Sigma Plot 10 software. Virtual water content (VWC) was calculated according to Sun at al. (2013) as follows:

$$\textbf{Virtual water content}(\textbf{VWC}) = \frac{\text{Water requirement } (\text{m}^3\ \text{ha}^{-1})}{\text{Grain productivity per unit area } (\text{tons ha}^{-1})} \qquad (2)$$

Salt tolerance index (STI) was calculated as outlined by Poudel et al. (2021) as follows:

$$\textbf{Salt tolerance index} = \frac{\text{Grain yield under non stressed conditions} \times \text{grain yield under stress}}{\text{Grain yield under non stressed conditions}^2} \qquad (3)$$

$$\textbf{Harvest index}(\textbf{HI}) = \frac{\text{Grain productivity per unit area}(\text{tons ha}^{-1})}{\text{Biological yield per unit area}(\text{tons ha}^{-1})} \times 100 \qquad (4)$$

Also, the financial revenues of deficit irrigations were estimated per hectare with the local currency (one dollar = 16.0 L.E.) as follows (1) land renting 16,500 L.E. (≈ 1031 $), (2) land preparation costs (fixed costs), and agricultural input prices (variable costs e.g. seeds, fertilizers, pesticides, fungicides, and labor costs) valued 9600 L.E (≈ 600 $). (3) Irrigation costs were 312 L.E. (≈ 19 $) for 50 % IR treatments while esteemed 468 L.E. (≈ 29 $) for 75 % IR treatments and 624 L.E. (≈ 37 $) for 100 % IR treatments, respectively. These calculations were based on the following: each irrigation required 24 L of fuel to lift or pump water (the cost of one liter of fuel was 6.5 L.E. (≈ 0.4 $)). No further costs are needed for the field-level water use. (4) The selling prices of one ton (megagram) of wheat grains was 4650 L.E. (≈ 260 $) and one ton of wheat straw was 1000 L.E. (≈ 62.5 $). Afterward, the net profit was determined according to the following equation:

$$\textbf{Net profit} = \textbf{Selling prices of seeds and straw} - \textbf{allfixedandvariablecosts} \qquad (5)$$

A novel model was introduced to calculate the overall efficiency of deficit irrigation (OEDI) in crop production comprising four basic components: grain yield (GY), stress tolerance index (STI), virtual water content (VWC), and financial revenues (FR). Their weights (Wt) were assessed via principal component analysis (PCA) using the SPSS statistical software. A unit-less factor (F) was also calculated for these parameters in which the ideal values, attained at non-stressful conditions, were donated by 100 while the non-ideal ones were calculated as reduction percentages (ranged from 0 to 100) from these ideal values. Scores of the four components (GY, STI, VWC and FR) were estimated by multiplying the weight of every component (calculated via PCA) by its unit-less factor and the summation of these scores represent the overall efficiency (OEDI) as presented in the equation below:

$$\textbf{Overall efficiency of deficit irrigation}(\textbf{OEDI}) = \sum \mathbf{F_{i\times}Wt_i} \qquad (6)$$

3. Results

3.1. Effects of deficit irrigations on growth parameters and yield components of the investigated wheat cultivars during two successive winter seasons of study

Deficit irrigations led to significant reductions in wheat straw, grain, and biological yields of all wheat cultivars during the two seasons of study (Table 1). For example, grain yield decreased significantly by 25.4–45.4 and 10.75–21.36 % in plants irrigated with either 50 or 75 % IR, respectively versus those irrigated with 100 % IR. In case of wheat straw, its yield also decreased in plants irrigated with 50 % IR by 10.5 and 32.1 % in the first and second seasons, respectively. Overall, the negative impacts of deficit irrigations were more noticeable on wheat grains than on straw; thus, the harvest index dropped considerably under deficit irrigations. Deficit irrigations also affected negatively each of spike length, spike weight (second season only), number of spikes per plant, number of wheat tillers per unit area, and 1000-grain weight (first season only), especially with decreasing the amount of irrigation water (50 % vs 75 % IR) (Table 2). Nevertheless, decreasing the amount of irrigation water from 100 to 75 % IR did not affect significantly the spike weights in the first growing season, while significantly decreased these weights in the second growing one. For plant heights, this parameter was not affected by deficit irrigation.

The highest grain yield was recorded for the cultivar Beniswief 5; while the two cultivars i.e., Giza 168 and Misr 1 recorded the highest straw yield. Although, there existed significant variations in all the investigated yield components among different wheat cultivars; yet, no definite trends could be deduced for these variations. Probably, some other factors such as the climate might contribute considerably to wheat growth and productivity. Refereeing to the interactions between wheat cultivar and deficit irrigations, it was found that the cultivar Giza 168 exhibited high sensitivity to deficit irrigations as its grain yield dropped by 31.4–60 % when plants irrigated with 50 % IR versus those received 100 % IR. On the other hand, saving 25 % of IR during the production of the

Table 1
Impacts of different irrigation levels on biological and grain yields of different wheat cultivars during two successive winter seasons.

Irrigation level	**Winter 2018/2019**				**Winter 2019/2020**			
	50 %IR	75 %IR	100 %IR	Mean	50 %IR	75 %IR	100 %IR	Mean
Biological yield (ton/ha)								
Giza 168	16.66±±0.98^{c-e}	18.09 + 1.02^{bc}	20.01 ± 1.64a	18.26A	10.08 ± 0.74 ^{h}	15.24 ± 0.92^{ef}	21.36 ± 1.94^{a}	15.56A
Misr 1	15.15 ± 1.52^{f}	18.33 ± 0.76^{b}	19.05 ± 1.06^{ab}	17.46AB	12.21 ± 0.83 ^{g}	14.28 ± 0.94^{f}	17.31 ± 1.16^{bc}	14.61A
Gemaiza 11	16.17 ± 1.17^{d-f}	16.67 ± 0.91^{c-e}	18.11 ± 1.34^{bc}	16.98B	12.11 ± 0.64 ^{g}	15.21 ± 1.14^{ef}	16.98 ± 1.08 ^{cd}	14.76A
Beni sweif 5	15.72 ± 1.25^{ef}	17.51 ± 0.84^{b-d}	19.16 ± 1.50^{ab}	17.46Ab	11.13 ± 0.83^{gh}	15.71 ± 1.60^{de}	18.405 ± 0.73^{b}	15.08A
Mean	15.89C	17.66B	19.08A		11.39C	15.11B	18.51A	
Grain yield (ton/ha)								
Giza 168	5.46 ± 0.43 ^{h}	6.75 ± 0.42^{ef}	7.94 ± 0.61^{b}	6.71B	4.29 ± 0.24^{d}	7.61 ± 0.52^{b}	10.41 ± 0.76^{a}	7.43AB
Misr 1	4.82 ± 0.38^{i}	6.95 ± 0.49^{d}	7.32 ± 0.58^{c}	6.36C	4.94 ± 0.18^{c}	5.51 ± 0.37^{c}	7.49 ± 0.59^{b}	5.97C
Gemaiza 11	6.39 ± 0.38 ^{g}	6.53 ± 0.38 ^{fg}	6.89 ± 0.38^{de}	6.60B	5.43 ± 0.31^{c}	7.62 ± 0.59^{b}	8.13 ± 0.69^{b}	7.065B
Beni sweif 5	7.07 ± 0.54^{d}	8.13 ± 0.57^{b}	9.68 ± 0.68^{a}	8.30A	5.16 ± 0.30^{c}	7.77 ± 0.48^{b}	10.23 ± 0.83^{a}	7.73A
Mean	5.93C	7.10B	7.95A		4.95C	7.13B	9.06A	
Straw yield (ton/ha)								
Giza 168	11.22 ± 0.81^{a}	11.34 ± 1.07^{a}	12.08 ± 0.83^{a}	11.55A	5.79 ± 0.31 ^{g}	7.635 ± 0.53^{de}	10.95 ± 0.55^{a}	8.13B
Misr 1	10.20 ± 0.76^{b}	11.39 ± 0.96^{a}	11.73 ± 0.94^{a}	11.10A	7.28 ± 0.52^{ef}	8.79 ± 0.62^{c}	9.83 ± 0.43^{b}	8.63A
Gemaiza 11	9.78 ± 0.69^{b}	10.16 ± 0.81^{b}	11.22 ± 0.86^{a}	10.38B	6.68 ± 0.41^{f}	7.59 ± 0.61^{de}	8.85 ± 0.51^{c}	7.71C
Beni sweif 5	8.66 ± 0.72^{c}	9.38 ± 0.59^{bc}	9.48 ± 0.73^{bc}	9.17C	5.97 ± 0.48 ^{g}	7.94 ± 0.70^{de}	8.16 ± 0.62 ^{cd}	7.37C
Mean	9.96B	10.56AB	11.13A		6.42C	7.98B	9.45A	
Harvest index								
Giza 168	32.67 ± 2.41^{d}	37.30 ± 1.86^{c}	39.66 ± 2.67^{c}	36.55BC	42.56 ± 2.81^{d-f}	49.90 ± 3.73^{b}	48.72 ± 3.57^{bc}	47.06B
Misr 1	32.07 ± 2.67d	37.89 ± 2.76^{c}	38.42 ± 2.27^{c}	36.13C	40.41 ± 3.27^{ef}	38.53 ± 2.61^{f}	43.23 ± 3.81^{de}	40.73C
Gemaiza 11	39.52 ± 2.94^{c}	39.16 ± 3.06^{c}	38.03 ± 1.98^{c}	38.90B	44.87 ± 2.92 ^{cd}	50.11 ± 4.37^{b}	47.88 ± 3.51^{bc}	47.62AB
Beni sweif 5	44.94 ± 1.68^{b}	46.45 ± 3.09^{b}	50.51 ± 3.81^{a}	47.30A	46.38 ± 2.88^{b-d}	49.47 ± 3.90^{b}	55.59 ± 4.08^{a}	50.48A
Mean	37.30B	40.20A	41.66A		43.56B	47.00A	48.86A	

*Similar letters indicate no significant variations among treatments.

Table 2
Impacts of different irrigation levels on plant growth parameters and yield components of different wheat cultivars during two successive winter seasons.

Irrigation level,	**Winter 2018/2019**				**Winter 2019/2020**			
	50 %IR	75 %IR	100 %IR	mean	50 %IR	75 %IR	100 %IR	mean
Plant height, cm								
Giza 168	94.9 ± 4.2^{a}	95.4 ± 3.9^{a}	99.6 ± 3.8^{a}	96.63AB	85.3 ± 5.2^{c}	97.5 ± 4.8^{ab}	99.2 ± 5.1^{a}	94.0B
Misr 1	96.2 ± 5.1^{a}	102.2 ± 6.7^{a}	94.5 ± 4.5^{a}	97.63AB	95.5 ± 4.0^{ab}	88.7 ± 3.6^{bc}	95.8 ± 4.3^{ab}	93.3B
Gemaiza 11	96.1 ± 4.6^{a}	100.5 ± 7.2^{a}	97.8 ± 5.4^{a}	98.13A	104.7 ± 7.2^{a}	99.2 ± 3.9^{a}	100.1 ± 5.3^{a}	101.3A
Beni sweif 5	96.8 ± 4.9^{a}	93.3 ± 5.2^{a}	88.2 ± 3.4^{a}	92.77B	98.4 ± 5.3^{a}	100.3 ± 6.6^{a}	102.0 ± 5.7^{a}	100.2A
Mean	96.0A	97.9A	95.0A		96.0A	96.4A	99.3A	
Spike length, cm								
Giza 168	10.0 ± 0.4^{e}	11.8 ± 0.6 ^{cd}	12.5 ± 0.5^{bc}	11.4B	15.3 ± 0.9^{a}	13.3 ± 0.9^{a}	12.7 ± 0.9^{a}	13.8AB
Misr 1	13.2 ± 0.6^{b}	11.2 ± 0.6^{d}	13.3 ± 0.7^{b}	12.6A	12.5 ± 0.6^{a}	14.9 ± 0.8^{a}	14.5 ± 0.8^{a}	14.0A
Gemaiza 11	16.0 ± 0.9^{a}	11.6 ± 0.7 ^{cd}	11.0 ± 0.3^{de}	12.9A	14.1 ± 0.7^{a}	12.3 ± 0.8^{a}	12.8 ± 0.5^{a}	13.1C
Beni sweif 5	11.5 ± 0.7 ^{cd}	11.0 ± 0.4^{de}	10.9 ± 0.4^{de}	11.1B	12.3 ± 0.5^{a}	14.6 ± 0.7^{a}	12.7 ± 1.2^{a}	13.2BC
Mean	12.7A	11.4C	11.9B		13.5AB	13.8A	13.2B	
Spike weight, g								
Giza 168	8.1 ± 0.7^{a}	8.7 ± 0.5^{a}	8.9 ± 0.6^{a}	8.6A	7.5 ± 0.7 ^{g}	11.7 ± 0.9^{b-e}	12.3 ± 0.8^{a-c}	10.5C
Misr 1	8.2 ± 0.8^{a}	8.8 ± 0.7^{a}	8.9 ± 0.7^{a}	8.6A	10.8 ± 0.8^{ef}	12.3 ± 0.8^{a-c}	12.8 ± 0.9^{a}	12.0A
Gemaiza 11	8.4 ± 0.4^{a}	8.7 ± 0.8^{a}	8.9 ± 0.6^{a}	8.7A	10.0 ± 0.8^{f}	11.7 ± 0.9^{b-e}	12.2 ± 0.7^{a-d}	11.3B
Beni sweif 5	7.5 ± 0.7^{a}	8.0 ± 0.6^{a}	8.1 ± 0.8^{a}	7.9B	11.2 ± 1.0^{de}	11.3 ± 1.1^{c-e}	12.5 ± 0.9^{ab}	11.7AB
Mean	8.1A	8.6A	8.7A		9.9C	11.8B	12.5A	
No. of spikelets/spike								
Giza 168	13.3 ± 0.7^{f}	13.5 ± 0.9^{ef}	14.9 ± 0.8^{e}	13.9C	15.6 ± 1.3^{c-e}	15.7 ± 0.8^{c-e}	17.2 ± 1.2^{ab}	16.1A
Misr 1	15.8 ± 1.1 ^{cd}	17.5 ± 1.3^{ab}	18.1 ± 1.3^{a}	17.1A	16.0 ± 1.2^{b-d}	16.2 ± 0.9^{a-d}	16.9 ± 1.2^{a-c}	16.4A
Gemaiza 11	14.8 ± 0.9^{de}	15.4 ± 1.2 ^{cd}	16.4 ± 1.1^{bc}	15.5B	14.3 ± 0.8^{ef}	15.2 ± 1.1^{de}	17.6 ± 1.3^{a}	15.7AB
Beni sweif 5	14.5 ± 0.8^{d-f}	14.7 ± 0.9^{d-f}	18.1 ± 1.4^{a}	15.8B	13.5 ± 0.9^{f}	15.5 ± 1.2^{c-e}	16.1 ± 1.0^{b-d}	15.0B
Mean	14.6C	15.3B	16.8A		14.9C	15.7B	17.0A	
No. of tillers / m^{2}								
Giza 168	301.3 ± 12.5 ^{g}	326.7 ± 22.1 ^{fg}	520.0 ± 42.1^{a}	382.7B	296.0 ± 20.6^{de}	320.0 ± 25.7 ^{cd}	336.0 ± 23.5^{bc}	317.3A
Misr 1	325.3 ± 20.3 ^{fg}	383.3 ± 30.4 ^{cd}	482.7 ± 39.6^{b}	397.1AB	276.0 ± 19.5^{e}	296.0 ± 25.9^{de}	400.0 ± 32.7^{a}	324.0A
Gemaiza 11	386.7 ± 25.1 ^{cd}	405.3 ± 35.3^{c}	454.7 ± 41.6^{b}	415.6A	237.3 ± 18.6^{f}	300.0 ± 28.6^{de}	358.7 ± 30..5^{b}	298.7C
Beni sweif 5	338.7 ± 2.7^{ef}	368 ± 29.5^{de}	457.3 ± 36.1^{b}	388.0B	274.7 ± 20.1^{e}	297.3 ± 26.7^{de}	353.3 ± 29.5^{b}	308.4AB
Mean	338.0C	370.8B	426.68A		271.0C	303.3B	362.0A	
1000-garin weight (seed index)								
Giza 168	46.7 ± 3.9^{bc}	50.0 ± 2.9^{ab}	50.0 ± 3.8^{ab}	48.9A	40.0 ± 2.2^{e}	46.7 ± 3.1 ^{cd}	53.3 ± 3.1^{ab}	46.7B
Misr 1	43.3 ± 3.5 ^{cd}	46.7 ± 3.8^{bc}	53.3 ± 4.2^{a}	47.8AB	43.3 ± 3.1^{de}	46.7 ± 2.6 ^{cd}	46.7 ± 2.5 ^{cd}	45.6B
Gemaiza 11	40.0 ± 2.4^{d}	46.7 ± 3.9^{bc}	53.3 ± 3.6^{a}	46.7AB	40.0 ± 2.8^{e}	50.0 ± 4.1^{bc}	50.0 ± 3.8^{bc}	46.7B
Beni sweif 5	43.3 ± 3.6 ^{cd}	43.3 ± 2.4 ^{cd}	50.0 ± 3.9^{ab}	45.5B	43.3 ± 2.9^{de}	53.3 ± 3.6^{ab}	56.7 ± 3.9^{a}	51.1A
Mean	43.3C	46.7B	51.7A		46.7A	47.5A	48.3A	

*Similar letters indicate no significant variations among treatments.

cultivar Benisweif 5 recorded comparable grain yield with some other cultivars such as Misr 1 and Gemaiza 11 that received their full irrigation requirements.

3.2. Effects of deficit irrigations on osmoprotectants (proline) and antioxidant enzymes in shoots of wheat cultivars during the two successive winter seasons

Osmoprotectants (proline) and antioxidant enzymes such as peroxidase (POX) and catalase (CAT) were a matter of concern in the current study because their changes signify the potential physiological comebacks of wheat cultivars towards stress conditions. Results obtained herein indicate that proline and antioxidants increased significantly in plant shoots subjected to water stress during the two seasons of study following the pattern of 50 % IR > 75 % IR > 100 %IR (Fig. 1). In particular, the values of both proline and catalase enzyme activity were higher in the first growing season than in the second one; while the activity of peroxidase enzyme was higher in the second growing season versus with the first one.

Variations in antioxidant enzymes were almost insignificant among the investigated cultivars, whereas proline were found at relatively higher content in shoots of Giza 168 and Misr 1 cultivars versus the other two cultivars. Interactions between irrigation levels and cultivars on proline and antioxidant enzymes were also insignificant.

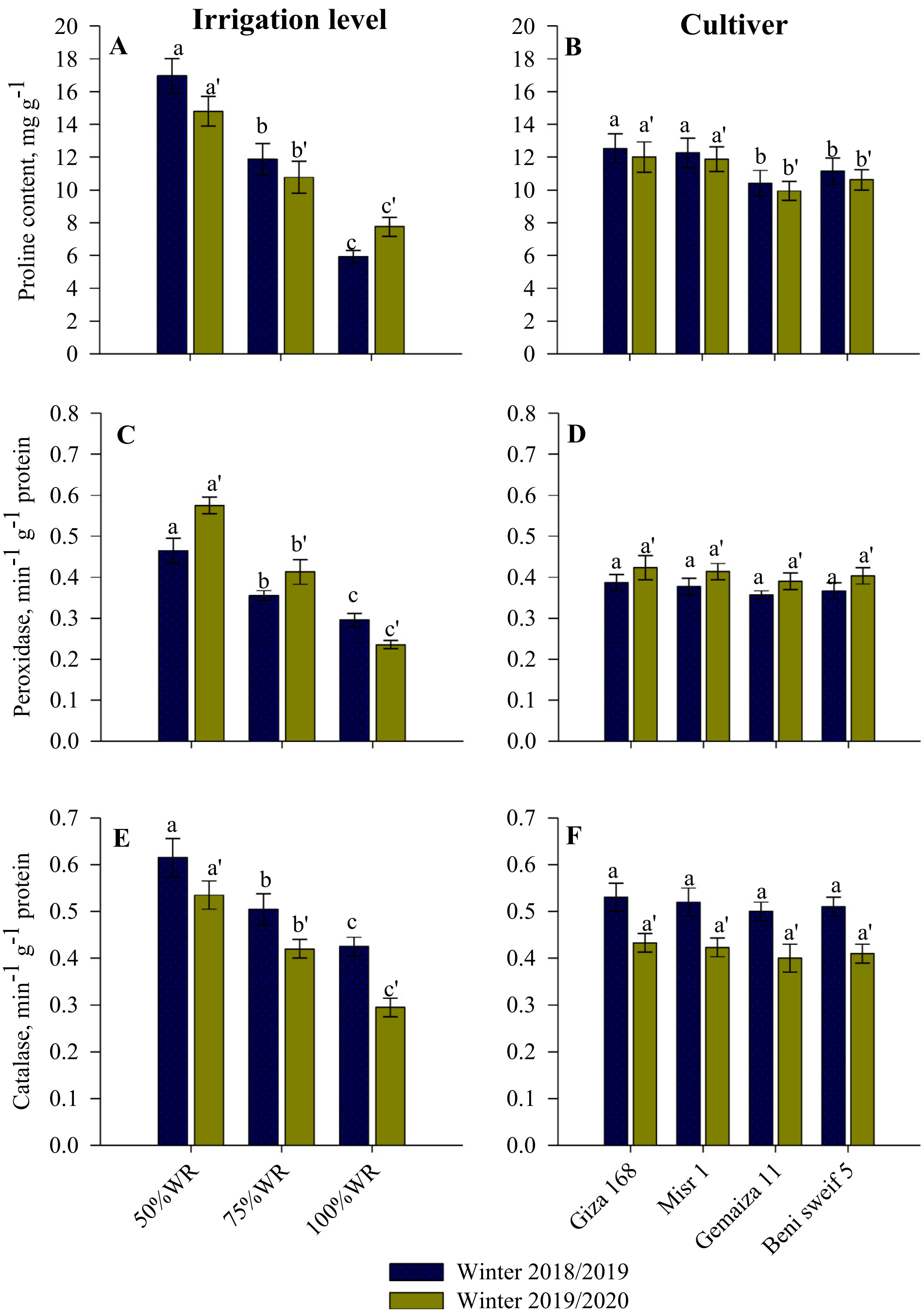

Fig. 1. Effects of deficit irrigations on proline content, peroxidase, and catalase activity in shoots of wheat cultivars during two successive winter seasons of study. Similar letters indicate no significant variations among treatments.

3.3. Effects of deficit irrigations on NPK contents within shoots of wheat cultivars (80 days after planting) during the two successive winter seasons.

Deficit irrigations led to significant reductions in NPK contents within wheat shoots after 80 days of planting (Table 3). These reductions became more noticeable with decreasing the irrigation level and followed the sequence of 50 %<75 %<100 % of IR. In this context, NK contents in plant tissues did not vary significantly among the investigated wheat cultivars during the two seasons of study, or even due to the interactions between irrigation levels and wheat cultivars. In case of P, its content exhibited the higher values in Benisweif5 in the first growing season, followed by Giza 168 and Gemaiza 11, then Misr 1; while the highest increases of P-shoot, in the second growing season, were detected in both Giza 168 and Beni sweif5, with no significant variations between these two cultivars. Concerning the interactions between deficit irrigations and wheat cultivars, it was found that the highest increases in P-shoot, in the first growing season, were recorded in Beni sweif5 (+100 % IR), followed by each of Giza 168 (+100 % IR), Misr 1 (+100 % IR) and Gemaiza 11 (+100 % IR), with no significant variations among these treatments. In the second season, the highest increases were recorded for both Benisweif 5 (+100 % IR) and Giza 168(+100 % IR) with no significant variations between these two treatments. A point to note is that Giza 168 (+75 % IR), Gemaiza11 (+75 % IR) and Beni sweif 5 (+75 % IR) recorded comparable P-shoot contents with Misr 1 (+100 % IR) and Gemaiza 11 (+100 % IR).

3.4. Effects of deficit irrigations on virtual water content and the stress tolerance of different wheat cultivars during two successive winter seasons.

Decreasing the irrigation level for wheat plants from 100 % to 75 % of IR led to concurrent significant reductions in wheat virtual water content (VWC) during both seasons of study (Fig. 2). Further reduction in irrigation level i.e. 50 %IR led to simultaneous drops in values of wheat VWC. The stress tolerance index (STI) was also considered in our calculations and its results reveal that STI decreased significantly for all cultivars when subjected to deficit irrigations, particularly 50 % IR. Concerning VWC and STI indexes, Misr 1 recorded the highest VWC values during the two seasons of study while exhibited the least STI ones. In contrast, Benisweif 5 recorded the least VWC values while displayed the highest STI ones.

Concerning the interactions between deficit irrigations and wheat cultivars, our results reveal that the highest values of virtual water content (VWC) were recorded for Gemaiza 11 cultivar during the first growing season when irrigated with 100 % IR while this cultivar presented low salt-tolerant index value (Fig. 3). In the second growing season, the highest VWC was noted for Giza 168 irrigated with 75 % IR. Also, this cultivar recorded the least STI values. Generally, the least VWC values and the highest STI ones were recorded for Giza 168 (Bread wheat cultivars) and Benisweif 5 (durum wheat cultivars) during both seasons of study..

3.5. Net profit and the overall efficiencies of wheat production under deficit irrigations systems during the two winter seasons.

The highest net profit was recorded for plants irrigated with 100 % IR followed by those irrigated with 75 % IR then 50 % IR (Fig. 3C). In particular, the highest net profit in the first growing season was attained for Benisweif 5 cultivar while both Giza 128 and Benisweif 5 cultivars recorded the highest net profits in the second growing season. To estimate the overall efficiency of deficit irrigations (OEDI) on wheat productivity, the following markers were taken into account: (1) grain cultivar productivity, (2) stress tolerance index, (3) virtual water trade content, and (4) the net profit. The weights of the four components were then assessed via PCA (initial Eigenvalue > 1) and these components represented 61 and 90 % of the variance of data. Afterward, the OEDI calculations were considered (Fig. 1D), which indicate that the overall efficiency decreased extensively with deficit irrigations, especially for 50 %IR. It is worthy to mention that Benisweif 5 recorded the highest efficiencies on basis of OEDI calculations (in the first growing season) while Giza 128 recorded the highest efficiency in the second growing season.

4. Discussion

4.1. The impacts of deficit irrigations on wheat growth and productivity

Wheat growth and productivity decreased significantly under deficit irrigations in the following order: 50 % IR < 75 % IR < 100 % IR. In this context, wheat grains were more adversely

Table 3

Concentration N, P and K (g kg^{-1}) in wheat shoots (80-day-old) of wheat cultivars during two successive winter seasons of study.

Irrigation level	Winter 2018/2019				Winter 2019/2020			
	50 %IR	75 %IR	100 %IR	Mean	50 %IR	75 %IR	100 %IR	Mean
Concentration N (g kg^{-1})								
Giza 168	19.53 ± 0.91^{a}	26.82 ± 1.24^{a}	35.27 ± 2.70^{a}	27.20 A	21.11 ± 2.50^{a}	29.76 ± 1.93^{a}	36.62 ± 2.40^{a}	29.16 A
Misr 1	19.95 ± 0.84^{a}	26.11 ± 1.61^{a}	35.48 ± 1.98^{a}	27.18 A	21.84 ± 1.83^{a}	29.27 ± 2.11^{a}	36.83 ± 2.11^{a}	29.31 A
Gemaiza 11	17.21 ± 0.83^{a}	24.46 ± 1.83^{a}	33.23 ± 1.34^{a}	24.96 A	19.58 ± 1.30^{a}	27.55 ± 1.83^{a}	34.71 ± 1.76^{a}	27.28 A
Beni sweif 5	18.64 ± 0.92^{a}	25.67 ± 1.71^{a}	34.85 ± 1.40^{a}	26.38 A	20.92 ± 2.18^{a}	28.63 ± 2.23^{a}	35.28 ± 1.95^{a}	28.27 A
Mean	18.83C	25.77B	34.71 A		20.86C	28.80B	35.86 A	
Concentration P (g kg^{-1})								
Giza 168	2.47 ± 1.58^{ef}	5.03 ± 3.01^{d}	7.11 ± 5.72^{b}	4.87B	3.65 ± 2.13^{f}	7.83 ± 4.62^{bc}	8.56 ± 6.81^{ab}	6.68A
Misr 1	2.16 ± 1.35^{f}	4.38 ± 2.45^{d}	6.57 ± 4.31^{b}	4.37C	3.32 ± 2.06^{f}	5.67 ± 4.70^{d}	7.35 ± 5.62^{c}	5.44B
Gemaiza 11	2.58 ± 1.98^{ef}	4.91 ± 3.27^{d}	7.03 ± 4.50^{b}	4.84B	3.55 ± 2.11^{f}	7.36 ± 5.68^{bc}	8.12 ± 6.51^{bc}	6.34A
Beni sweif 5	2.93 ± 2.10^{ef}	5.84 ± 3.62^{c}	8.48 ± 5.47^{a}	5.75A	4.82 ± 3.86^{e}	7.31 ± 4.36^{c}	9.24 ± 7.36^{a}	5.19B
Mean	2.54C	5.04B	7.30A		3.83C	7.04B	8.34A	
Concentration K (g kg^{-1})								
Giza 168	12.86 ± 0.82^{a}	20.67 ± 1.67^{a}	30.91 ± 1.92^{a}	21.48A	18.34 ± 1.38^{a}	31.12 ± 2.7^{a}	34.78 ± 3.18^{a}	28.08A
Misr 1	12.51 ± 0.73^{a}	19.32 ± 1.38^{a}	29.85 ± 1.86^{a}	20.56A	17.42 ± 1.62^{a}	30.68 ± 2.13^{a}	33.64 ± 2.49^{a}	27.24A
Gemaiza 11	12.63 ± 0.81^{a}	20.44 ± 1.61^{a}	30.46 ± 2.41^{a}	21.17A	17.94 ± 1.53^{a}	31.63 ± 3.05^{a}	34.58 ± 3.08^{a}	28.05A
Beni sweif 5	11.19 ± 0.59^{a}	20.28 ± 1.72^{a}	29.12 ± 2.88^{a}	20.19A	17.85 ± 1.83^{a}	30.49 ± 2.64^{a}	33.25 ± 2.19^{a}	27.19A
Mean	12.29C	20.18B	30.09A		17.88C	30.98B	34.06A	

*Similar letters indicate no significant variations among treatments.

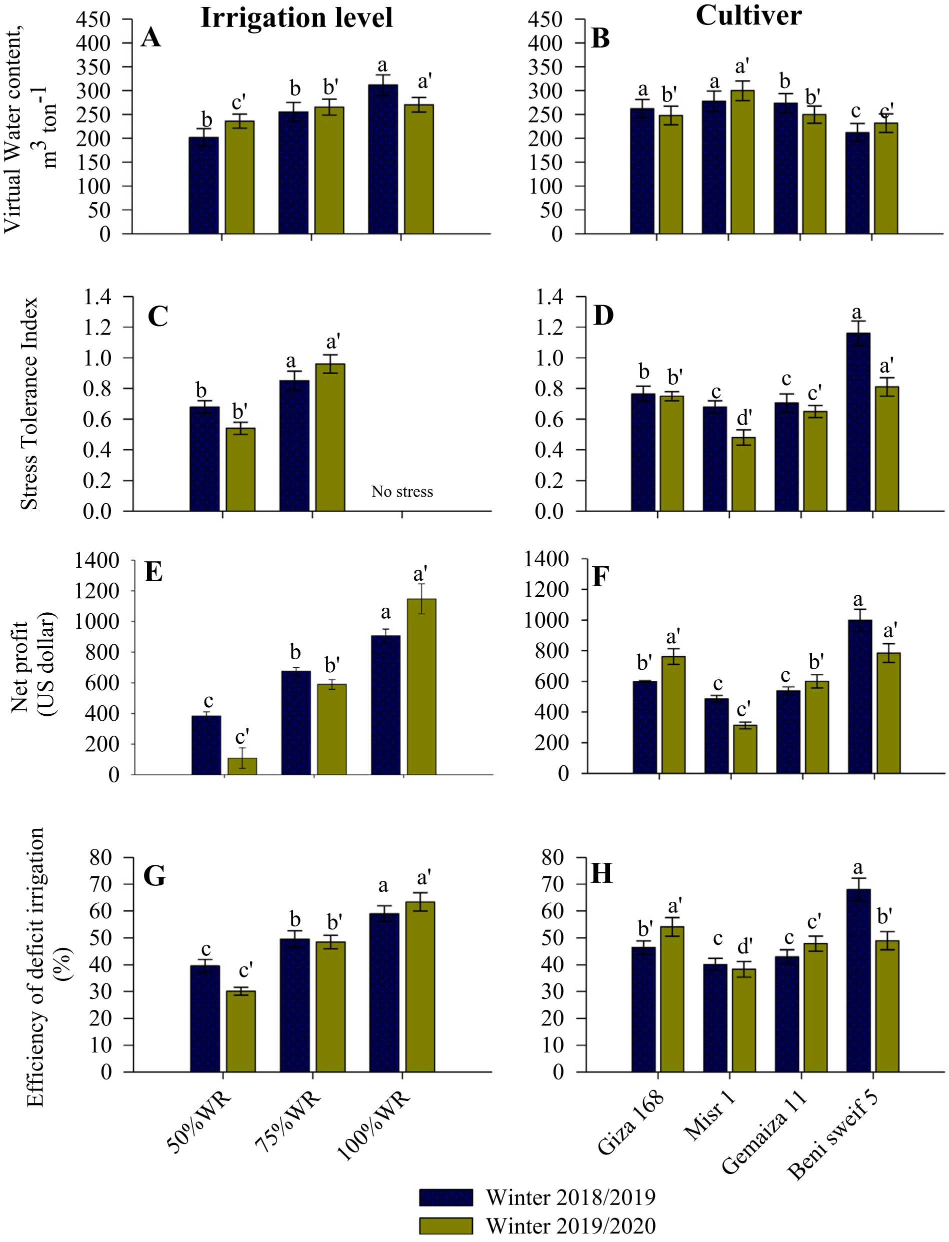

Fig. 2. Grand means of virtual water content (VWC), stress tolerance index (STI) and the overall irrigation efficiency (OEDI) among the investigated wheat cultivars as affected by deficit irrigations during the two winter seasons. Similar letters indicate no significant variations among treatments.

affected by deficit irrigation versus straw yield. Maybe, the impacts of deficit irrigations were more noticeable on the fillings and development of wheat grains (Gooding et al., 2003) than straw biosynthesis; accordingly, the harvest index values declined considerably. Similar results highlighted the negative effects of deficit irrigations on crop productivity e.g. wheat (Ding et al., 2021) and maize (Bassouny and Abbas, 2019) which contradict those of Ali and Talukder (2008) who found that deficit irrigations increase crop production. Yield components were also affected negatively by deficit irrigation such as spike length, spike weight, number of spikes per plant, number of wheat tillers per unit area, and 1000-grain weight, especially with using 50 % IR in plant irrigation, yet the parameter “plant height” was not affected significantly by deficit irrigation. Probably, the chromosomes responsible for plant height are stably expressed under water-limited and full irrigation environments (Li et al., 2015). Based on the above results, the first hypothesis becomes valid. Probably, deficit irrigation induces many physiological traits in grown plants (Chai, et al., 2015), thus, following up these changes were highlighted in the next section.

4.2. Impacts of deficit irrigations on plant nutritional status (NPK contents) and antioxidants in wheat shoots

Deficit irrigation led to considerable reductions in plant nutritional status i.e. NPK contents in shoots, especially with using 50 % of IR. These results agree with the findings of Hammad and Ali (2014) who noticed significant reductions (up to 50 %) in concentrations and uptake of NPK by wheat plants under deficit irrigations. Such reductions probably took place because nutrient mobility and supply to plant roots are related mainly to soil moisture (Eissa, et al., 2018). Thus, drought conditions lessened considerably the availability and uptake of nutrients by plants (Luo et al., 2018; Saud et al., 2020); while, contributing negatively towards

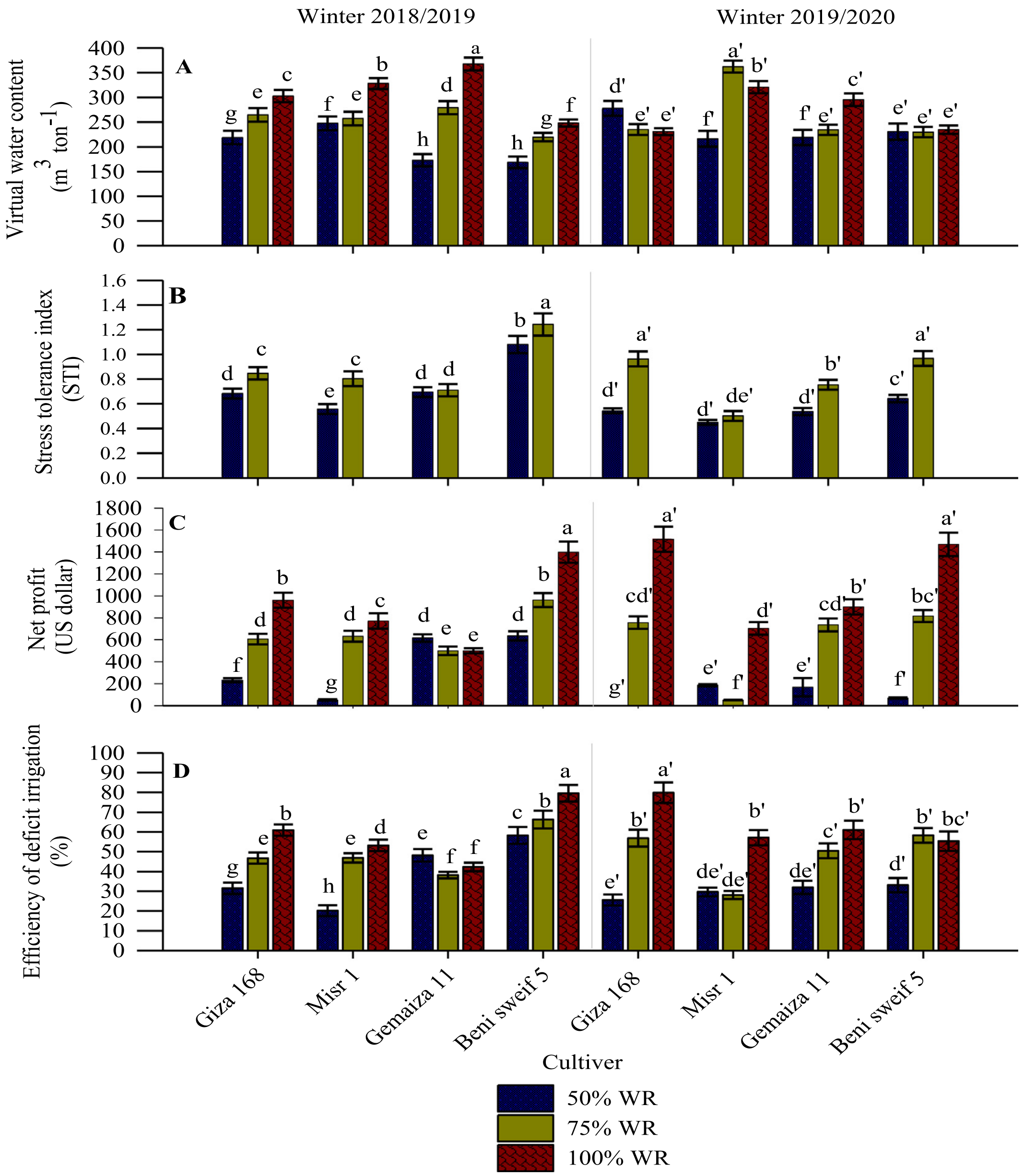

Fig. 3. Impacts of different irrigation levels on virtual water content (VWC), stress tolerance index (STI) and the overall irrigation efficiency (OEDI) during the two winter seasons of study. Similar letters indicate no significant variations among treatments.

reducing the yield (Ibrahim et al., 2020). Nevertheless, efficient nutrition is needed to sustain metabolic activities and lessen water stress impacts on crops (Saud et al., 2017).

On the other hand, deficit irrigations led to significant increases in osmoprotectants (proline) and antioxidant enzymes in wheat shoots such as peroxidase (POX) and catalase (CAT), following the pattern of 50 % IR > 75 % IR > 100 %IR. Similar results indicate that the activities of POX and CAT antioxidants increased significantly in wheat plants subjected to water stress (Farooq et al., 2020; Hafez et al., 2021). Probably, plants cope with these stress conditions via increasing activities of antioxidant enzymes (Farooq et al., 2017) to overcome the stress biomarkers that were produced during drought conditions (Nawaz et al., 2021) such as the biosynthesis of reactive oxygen and nitrogen species (Kapoor et al., 2019). In particular, proline acts as osmotic adjustment that stabilizes sub-cellular structure (Semida et al., 2020); hence increase plant tolerance to various abiotic stresses (Fahad et al., 2015; Semida, et al., 2020). On the other hand, the biosynthesis of osmoprotectants and antioxidants in stressed plants (irrigated with 50 and 75 % IR) modify plant metabolism and energy (Nowicka et al., 2018); and this may retard plant growth and productivity.

4.3. Impacts of deficit irrigations on contents of virtual water content, economic return revenue and the overall efficiency of deficit irrigations (OEDI)

Deficit irrigation led to considerable reductions in values of virtual water content (VWC) during both seasons of study, especially when using 50 % IR. These results; therefore, did not support the assumption which indicate that the productivity of a unit volume (one m^{-3}) of irrigation water could be higher under stressful drought conditions (Tambussi et al., 2007). Our calculations also considered the stress tolerance index (STI) and the financial revenue whose values also decreased notably in stressed plants. These calculations are valid because the costs of irrigation water are omitted in Egypt, and there are no volumetric measures for the field-level water use (Fuglie et al., 2021). Only the costs of "lifting water from a below-grade tertiary canal in the Nile Delta or the cost of managing water delivery from one of the raised tertiary canals or underground pipelines" are considered (Wichelns, 2002). Finally, the overall efficiency of deficit irrigations (OEDI) was estimated and its values decreased extensively with deficit irrigations, following the pattern of 50 < 75 < 100 %IR. These results did not confirm the second hypothesis. Thus, it can be deduced that deficit irrigations deemed not appropriate for rationalizing irrigation water during wheat production.

4.4. Impacts of deficit irrigations on the investigated wheat cultivars

The highest grain yield was recorded for the cultivar Benisweif 5 during the two seasons of study. Saving 25 % of IR during its production recorded comparable grain yield with other cultivars such as Misr 1 and Gemaiza 11 that received their full irrigation requirements (+100 %IR). This is a good point towards rationalizing irrigation water during production of a strategic crop like wheat. The highest P content was detected in shoots of Benisweif5 and this probably was the main reason beyond the variations that occurred in wheat growth and productivity under deficit irrigations. On the other hand, NK contents and antioxidants were comparable in wheat shoots among cultivars, yet for proline, it exhibited higher contents in shoots of both Giza 168 and Misr 1 cultivars.

The cultivar Benisweif 5 recorded the least virtual water content (VWC) values while exhibiting the highest stress tolerance index (STI) ones. These high values of STI are deemed as the most suitable cultivars under deficit irrigation systems (Farshadfar and Sutka, 2002; Moghaddam and Hadizadeh, 2002; Grzesiak et al., 2019).Also, Benisweif 5 recorded the highest efficiencies on basis of OEDI calculations in the first growing season, while Giza 128 recorded the highest efficiency in the second growing one. Therefore, these two cultivars are guaranteed as the most suitable cultivars for wheat production under deficit irrigation conditions in Egypt among the investigated cultivers.

5. Conclusion

Deficit irrigation was introduced by many researchers as one of the appropriate solutions for rationalizing irrigation water in arid regions. In this study, pros and cons of using this type of irrigation via 50 and 75 % IR were evaluated on wheat growth and productivity versus 100 % IR. Wheat growth and productivity decreased considerably under the stress conditions of deficit irrigations, moreover the amount of water used for production of one ton of grains increased markedly versus 100 % IR. Also, NPK contents decreased noticeably in plant shoot while the osmoprotectants (proline) and antioxidant enzymes (CAT and POX) increased under such stress conditions. On basis of the net profit and the overall efficiencies (OEDI) of deficit irrigations systems, Giza 168 (Bread wheat cultivars) and Benisweif 5 (durum wheat cultivars) could be the most suitable cultivars that can be grown under deficit irrigation. Finally, more studies are needed to investigate the effectiveness of using deficit irrigations in growing other crops on arid soils.

6. Ethics declarations

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CRediT authorship contribution statement

Ahmed M. Saad: Conceptualization, Software, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Amany K. Elhabbak:** Conceptualization, Software, Validation, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Mohamed H.H. Abbas:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Ibrahim Mohamed:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Mohamed A.E. AbdelRahman:** Methodology, Software, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Antonio Scopa:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Mohamed A. Bassouny:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sjbs.2022.103537.

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