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Productivity of some barley cultivars as affected by supplemental irrigation under rainfed conditions

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Abstract

Barley is widely cultivated in the northern coasts of Egypt and in the newly reclaimed lands. The goal of this study was response of some naked barley cultivars with high yield potential using supplemental irrigation under rain-fed conditions at Al-Kasr area, Marsa Matrouh, North-Western Coast of Egypt. The growth, yield, and drought-tolerance indices of Giza 129, Giza 130, and Giza 131, barley cultivars were estimated under rain-fed and supplemental irrigation regimes (SI0: rainfall only; SI1: two supplementally irrigations at tillering and heading stages; SI2: three supplementally irrigations at tillering, stem elongation, and heading stages). Agronomic traits including yield components and drought indices for the studied barley cultivars were assessed. The results displayed that Giza 131 gave a higher performance in most studied characters under rain-fed and irrigation regimes. Also, it produced the highest tolerance index (TOL), yield index (YI), harmonic mean (HM), stress susceptibility percentage index (SSPI), sensitivity drought index (SDI), mean productivity (MP), and geometric mean productivity (GMP). MP was positively correlated with YSI, GMP, DI, and HM. So, Giza 131 cultivar was identified as a drought-tolerant genotype. Moreover, the drought tolerance indices of TOL, YI, HM, SSPI, SDI, MP, and GMP are suitable for screening cultivars with high yields under stressed and non-stress conditions. The correlation analysis between the studied traits of barley indicated that highly significant positive correlation was obtained between number of spikes m^{-2} and grain yield. So, these traits are the most important components of the estimated grain yield of naked barley.

Keywords: Naked barley; rainfall; supplemental irrigation; grain yield; drought tolerant indices; stepwise regression analysis.
Abbreviations: TOL_tolerance index; YI_yield index; HM_ harmonic mean; SSPI_stress susceptibility percentage index; SDI_sensitivity drought index; MP_ mean productivity; GMP_ geometric mean productivity; NWC_north western coast; WUE_water use efficiency

Introduction

Improving crop yields is critical to meet the growing demand for food in the twenty-first century, which is driven by rising population and income (Pompeu et al., 2021). Assessment of production capacity of farms to boost the yield of important crops is one strategy that could solve this challenge (Chapagain and Good 2015). This can be accomplished by high-yield management techniques (Chen et al., 2014). Minimizing yield gaps in main crops through effective management strategies may result in great production providing environmental and economic benefits. Identifying yield gaps in field crops can help us to better understand yield variability, yield potential, and input efficiency, as well as point us in the right direction for increasing agricultural efficiency (Chapagain and Good 2015). Small grain cereals (rice, maize wheat, barley, rye, and oats) are the most important food sources, accounting for around 78% of all calories ingested by humans every day (FAO, 2011). Barley *(Hordeum vulgare* L.), the fourth most important cereal in the world, is a model species for temperate cereals (Wang, et al., 2019).

Barley is grown all over the world, in both high-yielding, high-input agricultural systems and low-yielding, low-input agriculture in a variety of climates. It provides cattle with feed and fodder, as well as food and drink for humans (Plaza-Bonilla et al., 2021). Barley was grown on 65,000 ha in Egypt, with an average grain yield of 3.65 ton per ha and a total production of 115,000 ton (FAO, 2017). In Nepal's high Himalayan region, naked barley is a traditional, culturally significant, climate-resilient, and extremely nutritious winter grain crop (Ghimire et al., 2019). Barley is the principal crop grown in Egypt, especially along with the northern beaches and in freshly reclaimed land soils (Sallam et al., 2019).

Incorporating barley into the flour mix for Baladi bread has emerged as a viable alternative in Egypt due to the crop's tolerance for development in marginal lands under rain-fed conditions (Hamwieh, 2021). High nutritional value, climate change resilience (adaptability to drought, salinity, and heat), low production costs compared to other cereals, and the potential to support livestock productivity through high yield and quality straw for livestock, as well as grain for chickens and sheep, are all advantages of barley (Lateef et al., 2021). If gradually introduced to scale, the inclusion of barley in the Baladi bread flour mix would provide significant economic benefits by closing the wheat yield gap, as current levels of wheat imports and related subsidies are taking a toll on the Egyptian economy, while also creating jobs and rural livelihoods (El-Metwally et al., 2011). In order to employ around 20% barley in composite flour, Egypt's barley production would have to rise and develop (El-Midany et al., 2019). To generate an additional 200-250,000 tons of barley, an area of up to 75,000 ha is necessary. Because barley uses less water than wheat, it might be gradually introduced on marginal and reclaimed regions with additional irrigation, as well as irrigated sites with excessive salinity, rather than being developed on wheat-specific grounds (Thabet et al., 2021).

In comparison to an alternate scenario for expanding wheat output, this increase of barley production would ensure a better level of national grain self-sufficiency while conserving the natural resource base and responding to climate change (Chapagain and Good 2015). Barley productivity grew from 0.44 ton per hectare in 1986-1991 to 1.9 ton per hectare in 2008/2009 under rain-fed circumstances. The production of rain-fed barley in Egypt is great when compared to other wet locations in the world, where the average rainfall surpasses 200 mm, despite the fact that Egypt's average rainfall is less than 130 mm (El-Metwally et al., 2011).

Drought, salinity, poor soil fertility, high temperatures and lack of suitable cultivars are all obstacles to barley farming in Egypt. Water is the defining factor for agricultural productivity in Egypt's rain-fed and desert agriculture, which is defined by precipitation. Because the average annual rainfall is less than 130 mm, the date of fall varies from year to year, as does the intensity (Abdelhameid and Kenawey 2019). In order to produce a cost-effective crop, it was necessary to use extra irrigation treatments. Under varied edaphic and climatic conditions, many researchers observed significant differences in the growth characteristics, yield attributes, and grain yield of naked barley varieties (El-Metwally et al., 2011). Supplemental irrigation is frequently the most critical limiting factor for cereal crop development and productivity in rain-fed regions, as well as the most expensive input for irrigated crops (Hamzei and Syedi, 2014). The insufficient soil moisture content in the root zone to meet crop water requirements is the principal barrier to grain output in the NWC region under rain-fed circumstances. Severe water stress is fairly common, and it frequently coincides with the most vulnerable stages of growth (Abu-Awwad and Kharabsheh 2000). As a result, crop yield potential can be increased if supplemental irrigation is administered in an acceptable amount and at the right time. The amount and timing of supplemental irrigation are designed to give adequate water during important growth stages to achieve maximum yield per unit of water (Milad, 2006).

As a result, identifying viable supplemental irrigation and determining the optimal cultivar that generates high economic yields in Egyptian rain-fed circumstances is critical for maximizing barley production under rain-fed conditions. This study aimed to analyse the responsiveness of different naked barley cultivars to supplemental irrigation under rain-fed settings and identify features that most directly influence grain yield under rain-fed conditions in the Al-Kasr area of Marsa Matrouh, Northwestern Coast of Egypt.

Results

Agronomic traits and yield components

Supplemental irrigation for barley production significantly improved the growth and productivity of barley cultivars (Figure 1, 2). Plant height as well as tillers number m^{-2}, spikes number m^{-2} and tillering index were significantly boosted by SI2 regimes, as their values gradually increased with increasing number of supplemental irrigations. The plants subjected to SI2 showed a significant increase in plant height traits by about 11.92 and 3.51% compared to the SI0 and SI1 regimes, respectively. Also, the number of tillers and spikes m^{-2} has been increased when exposed to SI2 treatment by 31.42 and 41.45%, higher than SI0 treatment, respectively. The C3-cultivar significantly produced the tallest plants which carry the highest tillers and spikes number m^{-2}. While, the C1-plants produced the lowest values of tillers and spikes number m^{-2}. Concerning the interaction, barley cultivars revealed great variations in response to supplementary irrigation, as the SI2×C3 treatment achieved the tallest plants, and significantly produced the maximum number of tillers and spikes m^{-2} relative to other treatments. But plants subjected to SI0×C1 significantly gave the lowest tillers (97.05) and spikes number m^{-2} (69.52).

The spike characters and grain weight values presented in Figure 2 revealed that spike length, spikelet number spike^{-1} and number of grains spike^{-1} traits significantly increased when receiving the SI2 regime. In comparison to SI0-plants, spike length was increased by 22.26%, resulting in more spikelets per spike (19.91%) and grain per spike (25.2%). Also, the weight of 1000-grain has been significantly affected by supplemental irrigation, as the heaviest grains were obtained by SI2-plants (38.04 g). On the other hand, the lowest values were given by SI0-plants (33.26 g) in this respect. The C1-plants significantly showed the tallest spikes. While, C3-plants have fewer short spikes than C1-plants, but carry more spikes and grains number along with the heaviest weight of 1000-grains relative to other cultivars.

The treatment of SI2×C3 maximized spike length, spikelets number spike^{-1}, and number of grains spike^{-1} traits as well as 1000-grain weight values but with non-significant difference compared to other treatments. The lowest spike length, spikelets number spike^{-1}, and number of grains spike^{-1} traits as well as weight of 1000-grain values were given by the treatment of SI0×C2 (55.07 cm, 21.37, 29.02 and 31.65 g, respectively).

Results in Figure 3 present the biological, straw and grain yields of barley cultivars in response to supplementary irrigation regimes. The biological, straw, and grain yields revealed a gradual and significant increase with increasing supplemental irrigation regimes, reaching the maximum values when barley plants received SI2-regime as produced 70.3, 72.62, and 65.46% higher for biological, straw and grain yields respectively, relative to SI0-regime. While, SI1 treatment significantly increased biological, straw and grain yields by 61.45, 62.6, and 59.43% respectively, higher than the SI0-regime. The C3-plants significantly presented higher yields of biological (5.87 t ha^{-1}), straw (3.93 t ha^{-1}), and grains (1.94 t ha^{-1}) than the other cultivars, while the C1-cultivar resulted in the lowest values in this respect.

Supplemental irrigation and cultivar interactions showed that the treatment of SI2×C3 significantly presented the highest biological (8.29 t ha^{-1}), straw (5.6 t ha^{-1}), and grain yields (2.69 t ha^{-1}). The lowest yields were reported by the treatment of SI0×C1-treatment which produced 1.83, 1.14, and 0.69 t ha^{-1} for biological, straw, and grain yields, respectively.

The presented results in Figure 4 showed the harvest and crop indexes response of naked barley cultivars to supplementary irrigation. Concerning harvest and crop indexes, SI2-treatment significantly reduced harvest and crop indexes, it decreased by 13.49 and 20.89 % respectively than SI0 which significantly resulted the highest harvest and crop indexes.

The highest harvest index of barley cultivars was observed by C1 and C2-cultivars, but with a non-significant difference among them. The C3-cultivar significantly recorded the lowest crop index. The treatment of SI2×C2 significantly resulted the lowest index values, but the highest harvest and crop indexes were given when plants were subjected to SI0×C2 treatment. SI2-treatment significantly recorded the highest WUE value compared to SI0, but with a non-significant difference with SI1-treatment. The C3-cultivar significantly gave the higher WUE value (2.36 kg m^{-3}), while the lowest value was obtained by the C1-cultivar. Regarding the interaction, the treatment of SI2×C3 significantly recorded the maximum WUE value (2.69 kg m^{-3}), while SI0×C1-treatment significantly produced the lower WUE value (1.43 kg m^{-3}).

Drought tolerance indices

The drought tolerance indices of barley cultivars under severe and moderate drought conditions are shown in Table 1. The TOL index demonstrated significant variations between cultivated seasons, with the TOL value increasing by 15.84 percent in the second season (Y2) compared to the first season (Y1). In terms of MP, YSI, GMP STI, HM, and DI values, there were no significant differences between Y1 and Y2, although Y1 gained the highest values in this respect.

Regarding the interaction, the treatment of SI0×C3 produced the highest TOL value, but the lowest value was given by SI1×C1 treatment. The indices of MP, GMP, and HM all exhibited higher values by SI1×C3-treatment. The treatment of SI0×C1 significantly exhibited the lowest values of MP, YSI, GMP, STI, and HM. Meanwhile, the highest value of SSPI was obtained by SI0×C1 treatment.

Pearson's correlation coefficient

Pearson's correlation coefficient was used for understanding of correlations between the examined traits and drought tolerance indices of three naked barley cultivars based on grain yield as affected by irrigation treatments (Fig 5, 6).

As for the examined traits of three naked barley cultivars, a significant positive correlation ($p<0.05$ or 0.01) obtained among all possible pairs for plant height; tillers number m^{-2}; spikes no. m^{-2}; tillering index (%); spikes length. cm^{-1}; spikelets no. per spike; grain no. per spike; 1000-grain weight (g^{-1}); grain yield (t ha^{-1}); biological yield (t ha^{-1}). Similarly, spikes length. cm^{-1}, grain No. per spike; 100-grain weight (g^{-1}); Grain yield (t ha^{-1}); Biological yield (t ha^{-1}) traits depicted a positive correlation ($p<0.05$ or 0.01). The spikelets no. per spike showed significantly positive correlation ($p<0.05$ or 0.01) with grain no. per spike; 100-grain weight (g^{-1}), grain yield (t ha^{-1}); biological yield (t ha^{-1}), and straw yield (t ha^{-1}). In this concern, grain no. per spike significantly positive correlation ($p<0.05$) with 100-grain weight (g^{-1}); grain yield (t ha^{-1}); biological yield (t ha^{-1}), and straw yield (t ha^{-1}). Also, 100-grain weight (g^{-1}) significantly positive correlated ($p<0.01$) with grain yield (t ha^{-1}); biological yield (t ha^{-1}), and straw yield (t ha^{-1}). Grain yield (t ha^{-1}) had significantly positive correlation with most of the examined traits ($p<0.05$ or 0.01), (Fig 5).

Likewise, water use efficiency showed significantly positive correlation with plant height; tillers number m^{-2}; spikes no. m^{-2}; tillering index (%); spikes length. cm^{-1}; spikelets no. per spike; grain no. per spike; 100-grain weight (g^{-1}); grain yield (t ha^{-1}); biological yield (t ha^{-1}); harvest index and crop index ($p<0.05$ or 0.01). However, a negative correlation ($p<0.05$ or 0.01) found between harvest and crop indices with plant height; tillers number m^{-2}; spikes no. m^{-2}; spikes length. cm^{-1}; spikelets no. per spike; grain no. per spike; 1000-grain weight (g); biological yield (t ha^{-1}) and straw yield (t ha^{-1}).

Generally, the highest positive correlation was observed between grain yield (t ha^{-1}) with most of the studied traits of three naked barley cultivars and water use efficiency under rainfed and supplementary irrigation (Fig 5).

As for the studied drought tolerance indices of three naked barley cultivars, TOL was significantly positive correlated with the SDI and SSPI. In this respect, MP showed significant positive correlation with YSI, GMP, STI, HM, and DI ($p<0.01$). Also, YSI showed significant positive correlation with GMP, STI, HM, and DI ($p<0.01$). In this concern, GMP significantly positive correlated with STI, HM and DI ($p<0.01$). The STI showed significant positive correlation with DI and HM ($p<0.01$). The HM showed significantly positive correlation with DI ($p<0.01$), and SSPI was positively and significantly correlated with SDI ($p<0.01$). A significant negative correlation ($p<0.05$ or 0.01) observed among all possible pairs for TOL, MP, YSI, GMP, STI, HM, and DI. Similarly, SDI and SSPI depicted a negative and significant correlation ($p<0.05$ or 0.01) with MP, YSI, GMP, STI, HM, DI (Fig 6).

Principal components analysis

PCs for the studied traits

Table S1 demonstrates how irrigation treatments affect the eight PCs for the three naked barley varieties (rainfed and supplementary irrigations). The eigenvalues of the first two recovered PCs (PC1 and PC2) are more than one (Eigenvalue >1), with values of 10.11 and 2.36, respectively. Other PCs' eigenvalues were less than one (Eigenvalue 1). As a result, the PC1 and PC2 were kept in the final analysis because the three PCs explain variance better than a single feature, expressing more variability, and support the choice of the trait with a positive loading factor.

The first three PCs explained 92.55% of the variance among the cultivars and additional irrigation treatments studied. Despite accounting for only 72.19% of overall variability in the observed data, PC1 contributed more to total variance than PC2 (16.85%) and PC3 (3.5%). As a result, the results of PC1 and PC2 can be used to summarize the original variables in any additional data analysis, as well as to explain total variance and PC collection.

The PC1 demonstrated positive relation for all analyzed parameters of naked barley and water use efficiency, except HI% and CI% of three naked barley cultivars under supplementary irrigation for the first nine components (Table S1).

The PC2 has identified all naked barley traits possessing positive loading factors and contribution to the variables except SN. $Spike^{-1}$, GN. $Spike^{-1}$ and BY (t ha^{-1}). Most traits had the highest positive loadings on PC3 and other PCs. Based on results of PCs for the investigated factors presented in Table (S2), the SI1×C3 and SI2 (C1, C2, and C3) influenced the PC1 and SI1×C1 influenced the PC2. The PC3 included SI0×C1, SI1×C1 and SI2×C1. Also, PC4 and PC5 consisted of SI1×C1 and SI2×C3 as well as SI0×C3, respectively. It had largely distributed and differentiated the variables and assessed features based on biplot diagram between PC1 and PC2. As a result, the first two PCs were used to create a biplot (Fig 7). The data of the analyzed variables showed a positive correlation among most of the measurements. However, the degree and consistency of the correlation varied. The biplot diagram showed how naked barley cultivars under additional irrigation contributed to the diversity of all variables tested (Fig 7).

PCs for drought tolerance indices

During the 2018/19 and 2019/20 growing seasons, PCs analysis was performed on 11 drought indices of three naked barley cultivars under moderate and severe drought circumstances (Fig 8). Based on drought indices combinations, PCA provided a clear distinction between naked barley cultivars and drought treatment to discover the indices that accounted much of the variation observed in naked barley cultivars. PCA1 and PCA2 both had eigenvalues greater than one (8.33 and 1.32, respectively), accounting for 75.71% and 12.01% of the variation, for a total of 87.72% of total variation (Table S3). While the eigenvalues of other PCs were less than one (Eigenvalue 1). As a result, the PC1 and PC2 were kept in the final analysis because the three PCs explain variance better than a single feature, expressing more variability and support the choice of the trait with a positive loading factor.

Despite accounting for just 75.71 percent of the total variability seen in the data, PC1 contributed more to total variance than PC2 (12.01%) and PC3 (7.5%). As a result, PC1 and PC2 results can be used to summaries the original variables in any additional data analysis, as well as to explain total variance and PC collection. Except for TOL, SSI, SSPI, and SDI, all the evaluated drought indices demonstrated a positive connection with the PC1. Except for DI and MSTI, the PC2 recognized all drought indices tested as having positive loading factors and contributions to the variables. Although, under the tested treatments, most indices had the largest positive loadings on PC3 and other PCs (Table S3).

The SI1×C1, SI1×C2, and SI2× C3 influenced the PC1 according to the results of PCs for the researched factors (SI× C) shown in Table (S4). SI0×C3, SI1×C2, and SI2×C3 were included in PC2. SI0×C1, SI0×C3, and SI0 (C1, C2, and C3) all had an impact on PC3. The variables and drought tolerance indicators were distributed and separated using a biplot diagram between PC1 and PC2. The first two computers were used to create a biplot (Fig 7). The majority of the drought tolerance measures studied showed a positive association. However, the degree and consistency of the correlation varied. The biplot diagram showed naked barley cultivars contributed to the diversity of all traits assessed during moderate and severe drought conditions (Fig 8).

Discussion

One of the biggest limiting constraints for crop production in arid and semiarid areas is a lack of water (Hellal et al., 2018). The unequal rain distribution over the growing season and the variation of precipitation from year-to-year are major obstacles to growth and production. Barley production under rain-fed conditions results in significant yield loss due to frequent drought (Hossain, 2012). Under the cultivated seasons and area conditions, the average annual precipitation was 159.25 and 89.50 mm, for the 1st and 2nd seasons respectively, compared to the annual average of 141 mm. Despite the prototype of rainfall revealing monthly variability within the two seasons. In the 1st season, the precipitation was 11.5% higher than the average annual precipitation, which is considered a moderate season. While the 2nd season precipitation was 36.5% less than the average annual precipitation, which is considered a dry season.

Drought is one of the most significant environmental factors that influences plant growth, development, and productivity (Hasanuzzaman et al., 2012). High temperatures or lack of precipitation cause sever drought stress on plants. Drought damage is proportional to the time of drought occurrence during the plant stages (Lopez et al., 2003; Hossain, 2012). Although the detrimental effects of drought on plant production can be mitigated by providing moisture to plants throughout the reproductive and grain-filling stages of their life cycle (Hossain, 2012). Increasing regimes of supplemental irrigation significantly improved the growth in barley cultivars under study. This may be a reason for the vital role of water in providing plants with the elasticity required for cell division, expansion, and elongation. That is leading to an increase in plant height, tillers, yield and yield related traits. Also, water is essential for all biochemical and physiological processes in plant cells and is considered the medium for all cellular functions' stimulation. Our results are in accordance with those of Khayatnezhad et al. (2011).

In the current study, the yield-components of naked barley cultivars, including spikes number m^{-2}, spikelets number $spike^{-1}$, number of grains $spike^{-1}$, and weight of 1000-grain were increased with increasing soil moisture. Such a result was obtained by Hu et al. (2015). Water deficits at various development and reproductive stages reduced spikes m^2 and floret fertility, then number of grains $spiked^{-1}$ (Maqbool, et al., 2015). The decrease in grain number $spike^{-1}$ in rain-fed treatment under research could be attributed to a lack of water during the booting period. Such results were obtained by Al-Ghzawi et al. (2019). The severe competition for assimilates between plant organs during vegetative growth and stem elongation was the reason for the number of grains $spike^{-1}$ depression (Richards et al., 2001; Semcheddine and Hafsi 2014). Under rain-fed application, the weight of 1000-grain barley has been markedly decreased than in SI regimes. The water deficit markedly decreased rain-fed crop yield and productivity due to its effects on uptake of nutrients, net assimilation, photosynthetic rate, and subsequently accumulation of biomass and productivity (Ullah et al., 2019). Water stress at the post-anthesis stage inhibited grain filling, then grain weight, and grain yield (Nazeri, 2005). In addition, water deficit decreases the photo-assimilates required for grain filling, decreases sink power for photo-assimilates absorbing, and decreases grain filling duration, as well as accelerates the plant's maturity and reduces photosynthesis rate, consequently reducing grain yield (Al-Ghzawi et al., 2019). In our study, SI regimes supplied increased 1000-grain weight, biological, straw and grain yields than the rain-fed-plants. These results are in accordance with Oweis (2012); Hussain et al. (2004); Wajid et al. (2004); Li et al. (2005). The yield component values revealed that under water deficit (S0), grain yield reduction was mainly due to reduction of spikes number m^{-2}, spikelets number $spike^{-1}$, number of grains $spike^{-1}$ and weight of 1000-grain. SI regimes improved the efficiency of WUE on grain yield. In all cultivars tested, low water conditions (SI0) reduced WUE value. Man et al. (2016) have previously reported an increase in WUE following SI treatments. An optimal genotype is a cultivar that can generate a satisfactory yield under both stressed and non-stressed conditions (Kirigwi et al., 2004). When compared to the rain-fed regime, all barley cultivars yielded more grain when provided with more soil moisture in our study.

Table 1. Drought tolerance indices of three naked barley cultivars based on grain yield (t ha^{-1}) for moderate (SI1)– sever (SI0) analysis in 2018/19 and 2019/20 growing seasons (Data collected over a two-year period).

	TOL	MP	YSI	SSI	GMP	STI	HM	DI	MSTI	SSPI	SDI
Year (Y)											
2018/19 (Y1)	0.914b	2.003a	0.631a	0.993a	1.902a	0.629a	1.815a	0.633a	1.003a	18.522b	1.829a
2019/20 (Y2)	1.086a	1.969a	0.570a	0.999a	1.841a	0.570a	1.731a	0.573a	1.009a	21.513a	1.942a
SI × C											
SI0× C1	1.715a	1.547d	0.287d	1.000a	1.287e	0.287d	1.071d	0.288b	1.002a	35.655a	2.117a
SI0× C2	1.441b	1.641d	0.391c	1.000a	1.471d	0.391c	1.320c	0.395b	1.010a	30.451b	1.970a
SI0× C3	1.736a	1.824c	0.358cd	0.998a	1.594c	0.357cd	1.397c	0.367b	1.025a	32.144ab	2.334a
SI1× C1	0.246d	2.282b	0.898a	0.989a	2.278b	0.897a	2.274ab	0.899a	1.001a	5.137c	1.506a
SI1× C2	0.330cd	2.196b	0.861ab	0.999a	2.19b	0.861ab	2.183b	0.862a	1.001a	6.941c	1.500a
SI1× C3	0.531c	2.426a	0.805b	0.993a	2.411a	0.804b	2.395a	0.806a	1.000a	9.779c	1.886a
P value											
Y	0.047*	0.442^{NS}	0.068^{NS}	0.943^{NS}	0.332^{NS}	0.146^{NS}	0.285^{NS}	0.244^{NS}	0.956^{NS}	0.048^{NS}	0.150^{NS}
SI x C	0.017^{*}	0.002^{*}	$<0.001^{**}$	0.998^{NS}	$<0.001^{**}$	$<0.001^{**}$	$<0.001^{**}$	0.011^{*}	0.980^{NS}	0.005^{*}	0.283^{NS}

TOL: tolerance; MP: mean productivity; YSI: Yield stability index; SSI: Stress susceptibility index; GMP: Geometric mean productivity; STI: Stress tolerance index, HM: Harmonic mean; STI: Stress tolerance index; DI: Drought resistance index; SSPI: Stress susceptibility percentage index; SDI: Sensitivity drought index. * and ** denote differences at the P≤0.05 and P≤0.01 probability levels, respectively. According to the Tukey-Kramer test (P≤0.05), means in each column followed by the same letter are not substantially different.

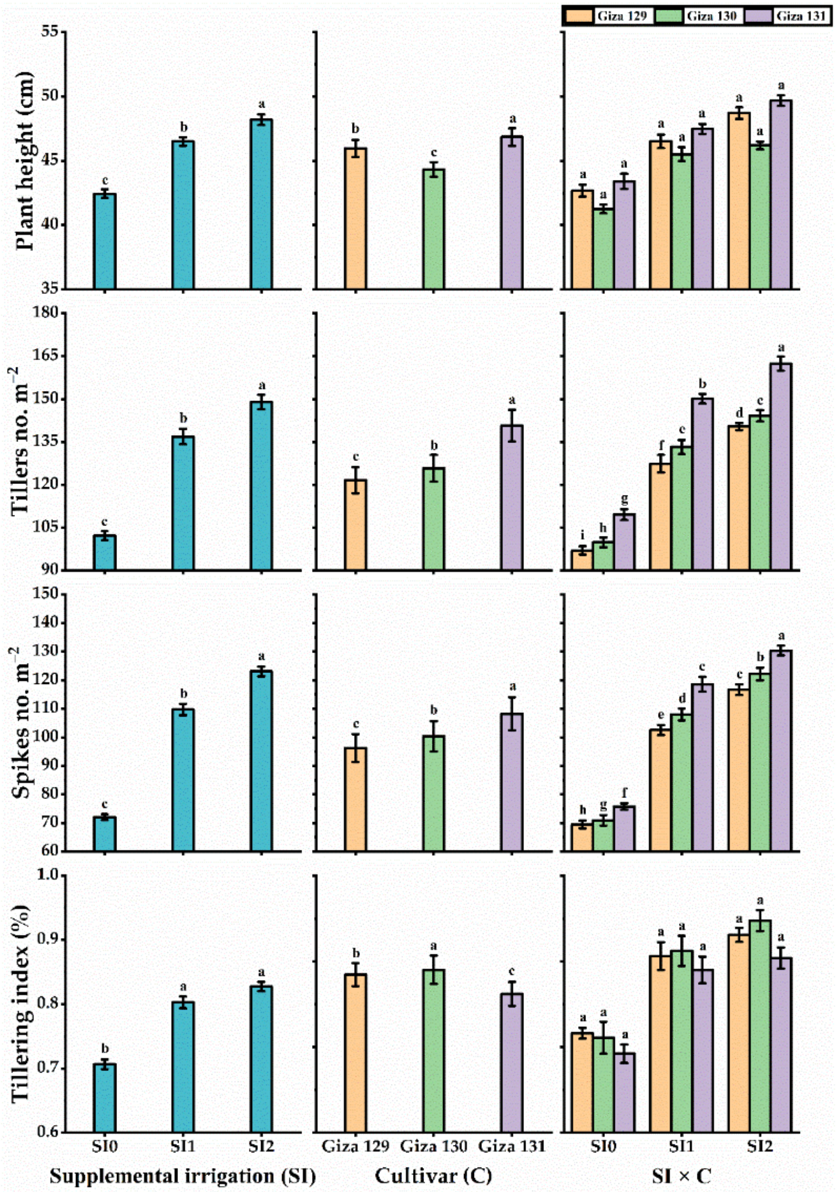

Figure 1. Naked barley agronomic traits of plant height (cm), tillers no m^{-2}, spikes no m^{-2}, and tillering index (%) affected by supplemental irrigation (SI), cultivars (C), and their interaction.

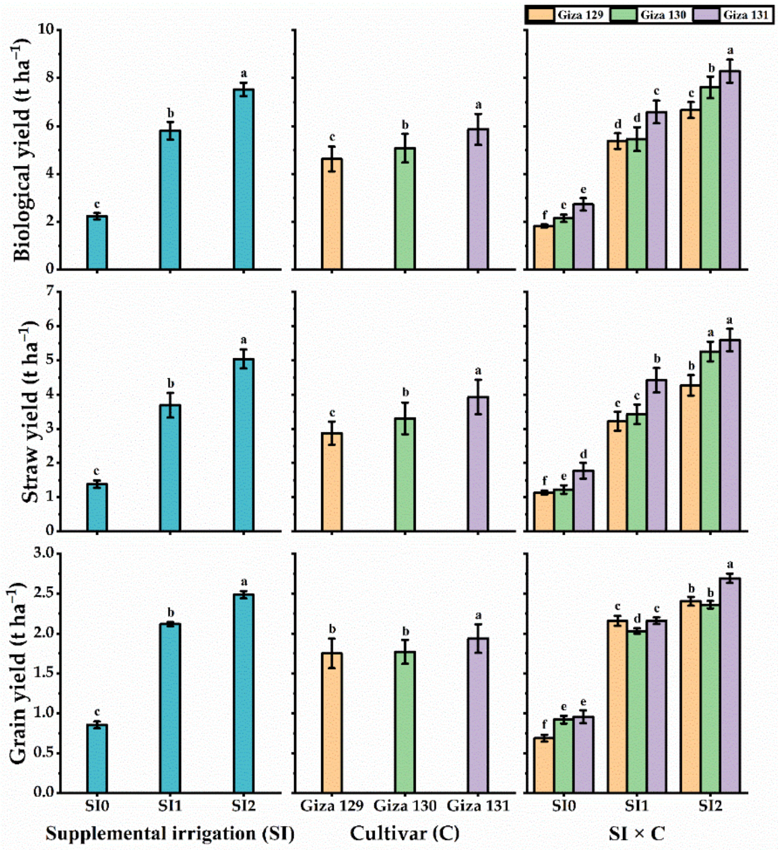

Figure 3. Naked barley yields of biological yield (t ha^{-1}), straw yield (t ha^{-1}), and grain yield (t ha^{-1}) affected by supplemental irrigation (SI), cultivars (C), and their interaction.

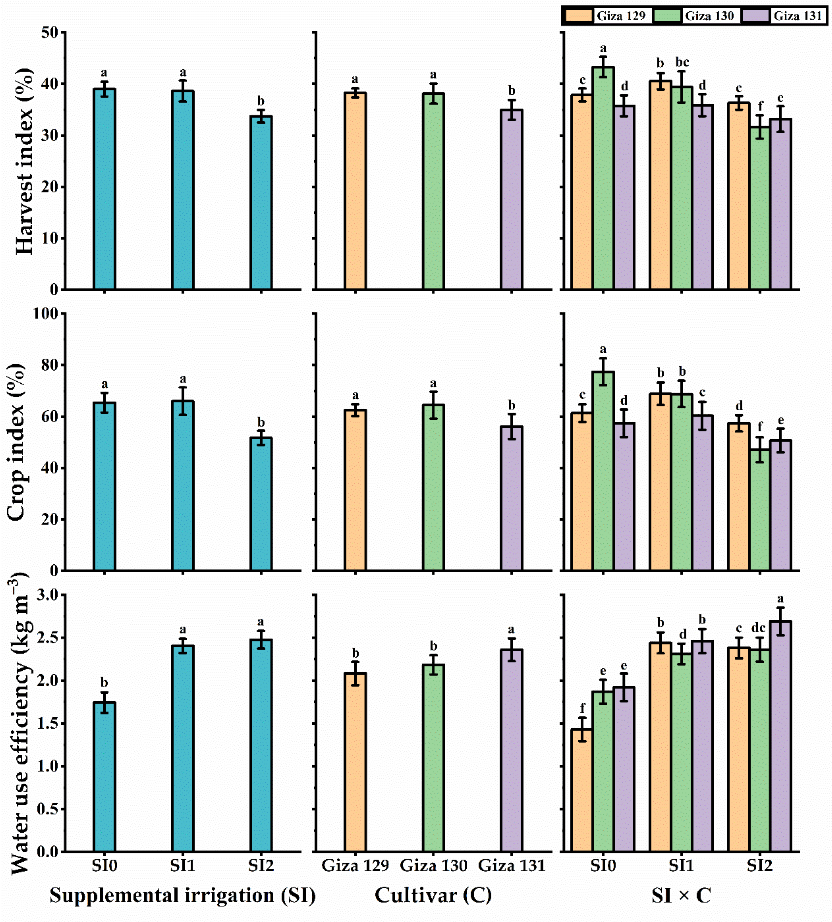

Figure 4. Naked barley yield indices of harvest index (%), crop index (%), and water use efficiency (kg m^{-3}) affected by supplemental irrigation (SI), cultivars (C), and their interaction.

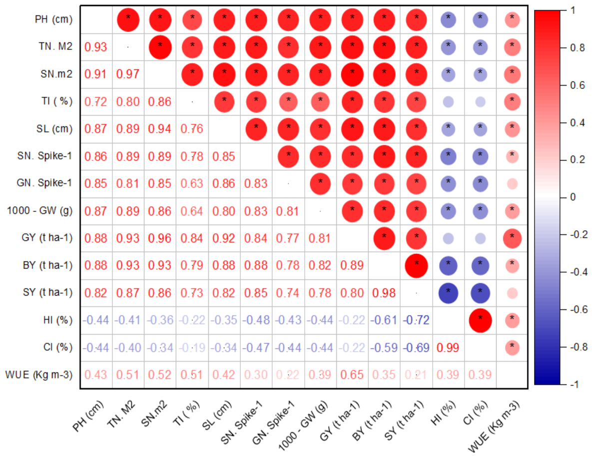

Figure 5. Plot describing Pearson's correlation between examined traits of three naked barley cultivars. PH: Plant height; TN: Tillers Number m^{-2}; SN: Spikes No. m^{-2}; TI: Tillering index (%); SL: Spikes length. cm^{-1}; SN. $Spike^{-1}$: spikelets No. per spike; GN. $Spike^{-1}$: grain No. per spike; 100-GW: 100-grain weight (g); GY: Grain yield (t ha^{-1}); BY: Biological yield (t ha^{-1}); SY: Straw yield (t ha^{-1}); HI (%) harvest index; CI (%): Crop Index; WUE: Water Use Efficiency (kg ha^{-1}). The big and medium blue (negative) and red (positive) circles show a substantial (*$P<0.05$) or extremely significant (**$P<0.01$) correlation, whereas the small blue (negative) and red (positive) circles show no correlation.

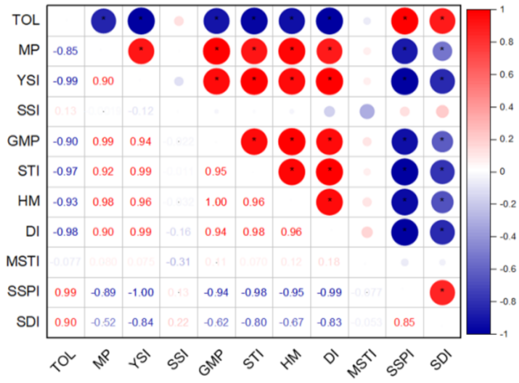

Figure 6. Plot describing Pearson's correlation between drought tolerance indices of three naked barley cultivars based on grain yield (t ha^{-1}). TOL: tolerance; MP: mean productivity; YSI: Yield stability index; SSI: Stress susceptibility index; GMP: Geometric mean productivity; STI: Stress tolerance index, HM: Harmonic mean; STI: Stress tolerance index; DI: Drought resistance index; SSPI: Stress susceptibility percentage index; SDI: Sensitivity drought index. The big and medium blue (negative) and red (positive) circles show a substantial (*P<0.05) or extremely significant (**P<0.01) correlation, whereas the small blue (negative) and red (positive) circles show no correlation.

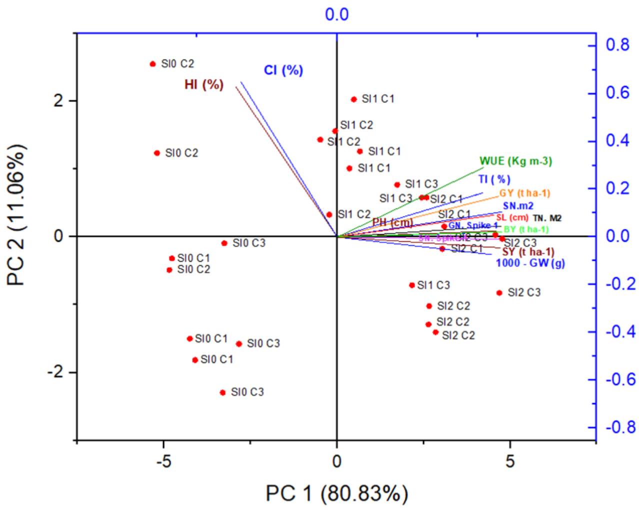

Figure 7. Diagram between PC1 and PC2 shows similarities and dissimilarities relationships of the examined traits of naked barley cultivars under irrigation treatments. PH: Plant height; TN: Tillers Number m^{-2}; SN: Spikes No. m^{-2}; TI: Tillering index (%); SL: Spikes length. cm^{-1}; SN. $Spike^{-1}$: spikelets No. per spike; GN. $Spike^{-1}$: grain No. per spike; 100-GW: 100-grain weight (g^{-1}); GY: Grain yield (t ha^{-1}); BY: Biological yield (t ha^{-1}); SY: Straw yield (t ha^{-1}); HI (%) harvest index; CI (%): Crop Index; WUE: Water Use Efficiency (kg ha^{-1}); SI0: rainfall treatment; SI1 and SI2: supplementary irrigation; C1: Giza 129 cultivar; C2: Giza 130 cultivar, C3: Giza 131 cultivar.

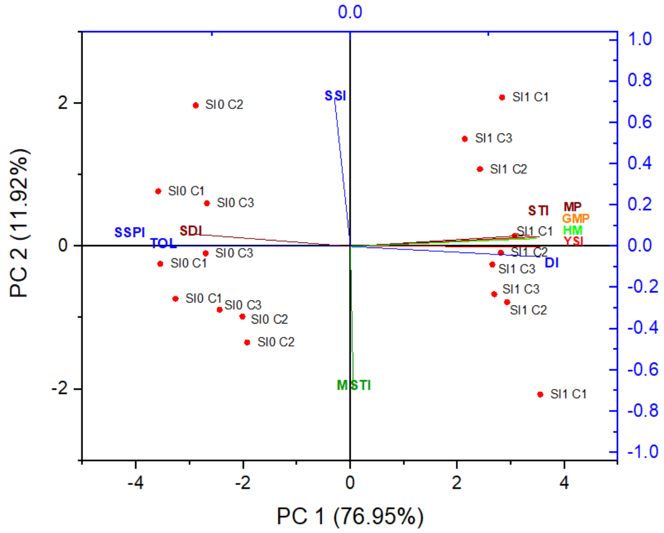

Figure 8. Biplot diagram between PC1 and PC2 shows similarities and dissimilarities relationships of 11 drought tolerance indices of three naked barley cultivars under irrigation treatments. SSI: stress susceptibility index; TOL: tolerance; MP: mean productivity; GMP: geometric mean productivity; STI: stress tolerance index; YSI: yield stability index; HM: harmonic mean; SDI: sensitivity drought index; DI: drought resistance index; SSPI: stress susceptibility percentage index, and GY: grain yield; SI0: rainfall treatment; SI1 and SI2: supplementary irrigation; C1: Giza 129 cultivar; C2: Giza 130 cultivar, C3: Giza 131 cultivar.

However, across the three water regimes, the examined cultivars indicated significant variances in most investigated traits. Giza 131 was the cultivar with the highest grain yield.
Higher biological and straw yields accompanied the productivity and grain yield improvements of Giza 131 cultivar. The discrepancies in grain yield are due to variances in the barley cultivars' tillers and spikes numbers m^{-2} and grains number $spike^{-1}$ potential. Giza 131 also had a better grain yield WUE and 1000-grain weight than Giza 130 and 129. Giza 131 was ranked highest, followed by Giza 130, then Giza 129, based on grain yield estimates for all cultivars examined.
The findings revealed a high association between spikes no m^{-2} and grain yield, as well as biological and grain yields. Toker and Cagirgan (2004) and Shrief et al. (2020) published similar findings, reporting a substantial link between biological and grain yields. The TOL index had a strong relationship with the SDI and SSPI. MP also had a significant and favorable relationship with the YSI, GMP, STI, HM, and DI. This suggests that barley cultivars' performance and productivity have improved under stressful situations.
Our findings clearly show that naked barley cultivars superiority well under SI regimes, as evidenced by their drought indices. The Giza 131 cultivar has the highest TOL, MP, GMP, HM, and SDI indices. In comparison to Giza 129 and 130 cultivars, Giza 131 is the most cultivar tolerant and produces higher yields under severe and moderate drought conditions. The indices YSI, SSI, and STI of the cultivar Giza 130 ranked as second after Giza 131. This indicates that this cultivar is adaptable to both stressed and non-stressed situations. Giza 129, on the other hand, was the least tolerant of the cultivars, with the lowest tolerance scores.

Materials and Methods

Characterization of the experimental field site

Two-year consecutive field trials (2018/19 and 2019/20 winter seasons) were conducted in Al-Kasr area, (latitude: 27° 8′ 27.60′′E and longitude: 31° 20′21. 28′′N) located in Marsa Matrouh, about 300 km of west Alexandria, on the North Western Coast of Egypt. The climatic conditions data for experimental period (November – May) during both seasons in this area, as well as the daily rainfall precipitation and wind speed are presented in Figure 1. The amount of rainfall precipitated was 159 mm/year in the 1st season and 89.5 in the 2nd season. The chemical and physical characteristics of the studied soil for 0.0-0.40 cm depth pre-cultivation in the first and second seasons were determined according to the standard methods of Klute (Klute, 1986), and are given in Table S5.

Experimental design and treatment details

A split-plot design with triplicates was used in the experiment layout. Three main plots were assigned to three supplemental irrigation treatments as: 1) rain-fed only by adding 650 m^3 ha^{-1} (SI0), 2) 2150 m^3 ha^{-1} (SI1), and 3) 2850 m^3 ha^{-1} (SI2). While, the three naked barley cultivars, Giza 129, 130, and 131 were distributed in the sub-plots. Each sub-plot was allocated a net area of 12 m^2 (3 m in length and 4.0 m in width), included 20 rows and 20 cm apart. All the plots were irrigated by 56 mm immediately after sowing to give good plant establishment.
The water used for supplemental irrigation was tap groundwater (ranging from 600 to 900 ppm) pumped from a local well. The source supplies water through an open gallery irrigation system. This technique is widely used in the north Sinai and the NWCZ. A gallery is an open channel, cut vertically down to a depth of one meter below the water table. Such galleries act as groundwater collectors. Supply water was added through a sprinkler irrigation system. The sowing date was after the 1st effective rainfall precipitation on December 13 in the 1st season (2018/2019) and November 12 in the 2nd season (2019/2020). Naked barley varieties (Giza 129, 130, and 131 cv.) were drilled at a rate of 85 kg/ha in rows 20 cm apart and 3 m long. Table S6 shows the full specifics of the supplemental irrigation treatments and several naked barley cultivars used in this experiment.

Agronomical crop management practices

The grains of naked barley cultivars used in the present study were secured from the Field Crops Research Institute, Ministry of Agriculture, Egypt. The released recommendations from the Egyptian Agriculture Ministry were followed. During the field preparation at sowing time, the experimental field was basally treated with 52.5 kgP2O5 ha^{-1} (169.4 kg calcium super monophosphate contained 15.5% P2O5). In addition, 180.4 kg N/ha^{-1} of nitrogen was sprayed (284.2 kg ammonium nitrate 33.5% N). It was given in two or three equivalent dosages, with additional irrigation times in between. In bare barley fields under Egyptian rain-fed circumstances, the other required agricultural techniques were carried out as usual.

Measurements

Agronomic traits and yield components

On the 28th and 9th April of the 2018/2019 and 2019/2020 seasons, the barley crop was handpicked at full maturity. Plant height (cm), spike length cm^{-1}, spikelets no $spike^{-1}$, and grains no $spike^{-1}$ were all measured on ten naked barley plants chosen at random from each subplot. To assess tillers no m^{-2}, tillering index, spikes no m^{-2}, and 1000-grain weight g^{-1}, all plants in m^{-2} were randomly picked from each plot. Plants in each sub-plot were harvested to determine grain, straw, and biological yields in the aggregate. The grain production per m^3 of water was also evaluated using the harvest index, crop index%, and WUE.

Drought tolerance indices

Using the formulae in Table S7, drought indices were derived for three naked barley cultivars based on grain yield (ton ha^{-1}). Ys, Yp, and Ýs, Ýp yields in stress and non-stress conditions for each genotype, as well as yields in stress and non-stress conditions for all genotypes, were also shown in the same Table.

Statistical analysis

Using GenStat Release 12.1 (PC/Windows, VSN international Ltd V. 2009, Hemel Hempstead, UK), all obtained data for various parameters was statistically evaluated using the technique of analysis of variance for split-plot design. For the data from the two seasons, a combined analysis was performed. The Bartlett test was used to check for homogeneity of error variances before doing a combined analysis over years (Steel et al., 1997). Tukey-Kramer was used as a post hoc test to compare the differences between treatment means (Gomez and Gomez 1984). The multicollinearity between interpretive qualities in the correlation matrix was detected using multicollinearity analysis. To decrease the dimensionality of data space, principal component analysis (PCA) was done based on a correlation matrix among several naked barley attributes and drought indexes, and a biplot was generated using the XLSTAT statistical programme (Version 2019, Excel Add-ins soft SARL, New York, NY, USA). The Origin v. 2021b SR2 programme was used to draw all figures (OriginLab Corp, Northampton, Massachusetts, USA).

Conclusion

Rain-fed crops are frequently exposed to water deficits that negatively impact yield potential, particularly when occurred at the reproductive and grain-filling stages. Thus, the consideration of barley yield variations under rain-fed and supplemental irrigation conditions is basic for genotype selection programs that are higher yielding with most drought tolerance. In this study, the analysis of grain yield and its component traits revealed that naked barley cultivars (Giza 129, 130, and 131) showed different responses to producing grain yield under stressed and non-stressed plants. The final yield of grains is impacted by spikes no m^{-2}, spikelets no $spike^{-1}$, grains no $spike^{-1}$, and the weight of 1000-grain. The Giza 131 cultivar presented better yields than other cultivars under rain-fed and supplemental irrigations. Furthermore, Giza 131 gave better performance under severe conditions as shown by drought tolerance indices. Also, the same cultivar appeared to have a higher TOL, MP, GMP, HM and SDI indices values. Correlation analysis revealed that spikes no m^{-2} grain, and biological yield had high significant positive correlation along with grain yield with biological yield.

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