

Article

Deficit Irrigation on Guar Genotypes (*Cyamopsis tetragonoloba* (L.) Taub.): Effects on Seed Yield and Water Use Efficiency

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Abstract: For guar, a well-known drought and heat-tolerant industrial legume with a spring–summer cycle, limited research has been conducted into measuring the effects of drought on yield potential. A two-year field experiment was conducted to explore the effects of different irrigation regimes on yield, yield components and water use efficiency (WUE) on five cultivars of guar (Kinman, Lewis, Matador, Monument, and Santa Cruz) in a semi-arid Mediterranean environment. Three different water replenishment levels were used: fully irrigated (I_H , 100% of the ET), and 50% (I_M) and 25% (I_L) irrigated. Seed yields ranged from 1.24 (I_L) to 3.28 t ha⁻¹ (I_H) in 2011, and from 0.98 (I_L) to 2.88 t ha⁻¹ (I_H) in 2012. Compared to I_H , the two-year average seed yield reductions for I_L and I_M were 49% and 26%, respectively. Lewis and Santa Cruz showed significantly greater grain yields under fully-watered and water-limited conditions. The number of pods per plant achieved the highest positive direct effects on seed yield ($r = 0.924^{***}$). The highest values of water use efficiency were observed in the I_L water regime (1.44 kg m⁻³ with increments in improved water use efficiency of +34 and +95% when compared with I_M and I_H , respectively).

Keywords: guar; deficit irrigation; yield; yield components; water use efficiency

1. Introduction

Guar (*Cyamopsis tetragonoloba* (L.) Taub.) is a well-known industrial legume species with a spring–summer crop cycle. It is among the most drought-tolerant, heat-tolerant row crops grown in the world [1]. It is mainly grown in semi-arid regions of India (80% of the world's production) and Pakistan (15%); the remaining 5% is located in the United States (Texas and Oklahoma) and Sudan [2]. Guar is an interesting sustainable crop for a wide range of environments, showing a low-input profile [3] and a good capability to adapt to different soil textures and to salinity and low-fertility soil conditions [4,5].

The importance of guar among industrial crops is due to the unique thickening ability and stabilizing, binding and strengthening properties of the seed galactomannans. These long branching polymers of mannose and galactose, contained in the endosperm, are widely used in food industries but also for paper, textiles, oil well drilling and fracking industries [6–10]. Guar-gum powder, in fact, has unique binding, thickening and emulsifying characteristics, which make it suitable for a wide range of uses. The industrial extraction of galactomannans is restricted to only a few crops which include guar, carob (*Ceratonia siliqua* L.), tara shrub (*Cesalpinia spinosa* L.), fenugreek (*Trigonella foenum-graecum* L.), and senna (*Senna occidentalis* L.). Among these, guar galactomannans demonstrate the advantage of a good solubility in relatively cold-water conditions, providing a valuable reduction of industrial costs.

Recently, guar has experienced a large increase in use in petroleum and natural gas extraction, which is currently by far the main use of guar gum [7].

Once the endosperm has been separated, the remaining seed coat and the germ represent a valuable protein-rich by-product which is useful as a feed supplement for animals [11,12].

Numerous research reports demonstrate the adaptability of guar to a Mediterranean environment [13–15]. In fact, guar thrives in hot climates. Undersander et al. [16] reported 30 °C as an optimal temperature for growth and development. Gresta et al. [17] indicated, for consistent germination, a threshold temperature higher than 20 °C for 6 h a day. In environments in which high temperatures are associated with potential drought, one of the major questions is the potential benefit of irrigation.

The limited availability of irrigation water worldwide requires fundamental changes in irrigation management and the application of water-saving methods. Moreover, the decrease in water availability has forced researchers to focus on increasing crop water use efficiency by improving either drought-tolerant varieties or crop and water management. Few reports quantify the effects of soil water status on guar. Alexander et al. [18] reported relatively low water requirements in guar but emphasized that an excess of water prolonged the vegetative growth stage. This study did not report on water use efficiency.

Venkateswarlu et al. [19] reported that water stress reduces the nitrogenase activity of nitrogen-fixing bacteria (*Bradyrhizobium*), which may reduce seed yield potential.

Thus, although guar is considered a drought-tolerant species, apart from the above few reports, few research works have been conducted to evaluate and quantify how much drought severity may diminish guar yield potential.

With this in mind, efforts in guar should focus on identifying genotypes with a high seed yield and high water use efficiency, which are often related with crop drought tolerance.

An experiment was conducted to evaluate the effect of water reduction on yield, yield components, WUE, and morphological parameters on five guar cultivars in a semi-arid Mediterranean environment.

2. Materials and Methods

2.1. Site Description and Materials

A two-year experiment (2011 and 2012) was conducted at the experimental farm of the Department of Agriculture Food and Environment of the University of Catania (Ispica, Sicily, South Italy, 36°50' N, 14°52' E, 330 m a.s.l.). The soil was classified as a clay loam soil and contained high percentages of clay (38%) and sand (37%). The dry soil bulk densities were 1.2 g cm⁻³ over a 0.9-m deep profile. The volumetric soil moisture content at field capacity and at permanent wilting point, determined using the pressure plate method, were 33.1 and 16.6%, respectively.

Five U.S. commercial guar cultivars (Kinman, Lewis, Matador, Monument and Santa Cruz), and three levels of irrigation (high, medium and low) were adopted as experimental factors. The treatment layout was a split-plot design, replicated three times, with irrigation as the main plot and cultivars as the sub-plot. Each experimental sub-plot was 20 m² (5 × 4 m) with 25 plants per m⁻².

Sowing was done manually on 20 May for both years. At sowing, to establish homogenous stands, soil water in the profile depth was replenished to field capacity in all treatments.

Throughout the growing season, a meteorological station located close to the experimental field recorded daily air temperature, air humidity, rainfall, wind speed and direction, and evaporation from a standard Class-A-Pan.

To guide the irrigation treatment applications, the open pan evaporation method was applied and the crop coefficients were determined from a model crop in dry, hot environmental conditions. As a model crop, we chose soybean as a legume crop with similar growing season and cycle length.

Evapotranspiration amounts were calculated with the following equation [20]:

$$ETc = E_{pan} \times K_p \times K_c \quad (1)$$

where ETc = crop evapotranspiration (mm), E_{pan} = cumulative evaporation amount from standard Class-A-Pan (mm), K_p = pan-coefficient, equal to 0.80 (average relative humidity 40%–70%, low wind speed) and K_c = crop coefficient, related to phenological phases.

The three irrigation levels were imposed using 100% of ETc for the highest irrigation amount (I_H) and 50 and 25% of I_H for medium (I_M) and low (I_L) replenishment levels, respectively. Irrigation was applied, using a surface drip system, when ~66% of available soil moisture was consumed in the root zone (0–0.90 m).

The water used during the whole crop cycle was calculated as follows [21]:

$$WU = I + R - dr - rf \pm \Delta w \quad (2)$$

where WU = water used in the whole crop cycle, I = irrigation water applied (mm), R = effective rainfall (>10 mm), dr = amount of drainage water (mm), rf = amount of runoff (mm), and Δw is the difference in terms of water content in the soil layer explored by roots (0–0.90 m) at sowing and harvesting time, measured gravimetrically. Since the amount of irrigation water was controlled, deep percolation and run off were assumed to be negligible. In the study, four different crop coefficients were adopted: 0.48 during the initial growth stage, 0.9 during the rapid growth, 1.09 in the medium maturity stage, and 0.45 during the late season stage.

The differential irrigation treatments started on 29 May for both years and ended on 17 September and 25 September in 2011 and 2012, respectively. Based on equation 1, 13 and 14 irrigations were required to satisfy the ETc requirements of guar in 2011 and 2012 crop cycle, respectively.

Before sowing, 7 l/ha of trifluralin was incorporated into the soil to control weeds. In addition, hand-weeding was performed as needed. At sowing, 20 kg ha⁻¹ of N (as starter fertilizer), 40 kg ha⁻¹ of P₂O₅ and 30 kg ha⁻¹ of K₂O were distributed and incorporated in the soil.

Leaf area was determined at the beginning of seed maturation, measuring all the leaves of five plants per plot, by means of Delta-T leaf area meter (Delta-T Devices Ltd., UK).

At harvest, seed yield was determined on a sampling area of 6 m² (3 × 2 m) in the central rows of each sub-plot to avoid any edge effect. Seed yield was adjusted to 13% moisture. The following parameters were recorded on a random sample of 20 plants per plot: number of fertile pods, number of seeds per pod, thousand seed weight, plant height. Harvest index was calculated as the ratio between seed yield and above ground biomass.

Water use efficiency (WUE kg m⁻³) was calculated from the seed yield and the water balance for each treatment.

2.2. Data Analysis

The analysis of variance was computed using DSAASTAT Excel statistical package [22] to assess differences between years (Y), irrigation regimes (I), cultivars (C) and their interactions. All factors were considered as fixed effects. Tukey's HSD (honestly significant difference) test was adopted to analyze statistical differences among treatments ($P < 0.05$) with DSAASTAT Excel statistical package [22].

2.3. Weather Conditions

The crop seasons were 143 and 136 days in 2011 and 2012, respectively. The first year showed an average temperature of 23.0 °C during the whole crop cycle, reaching maximum values during the months of July and August, with a peak value of 37.1 °C, and 26 days with day temperatures over 33.0 °C (Figure 1). No effective rainfall was recorded from sowing to late September. The second year was warmer (+1.1 °C vs. first year mean temperature) but no effective rainfall until the ripening period (17 mm). June, July and August recorded repeated temperature peaks (with the highest value

of 39.7 °C) and had over 40 days with day temperatures over 33 °C. Seasonal water use ranged from 863 (I_L) to 3455 m³ ha⁻¹ (I_H) in 2011 and from 1050 (I_L) to 3691 m³ ha⁻¹ (I_H) in 2012.

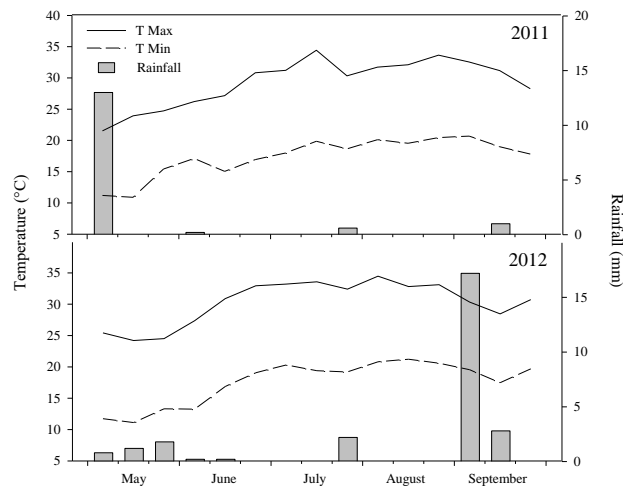


Figure 1. Meteorological data during the guar study period in 2011 and 2012, Ispica, Sicily.

3. Results

3.1. Yield and Yield Components

Yields for treatment averages ranged from 1.24 to 3.28 t ha⁻¹ in 2011, and from 0.98 to 2.88 t ha⁻¹ in 2012. The Y × C interaction (Table 1) was significant, however, for all cultivars except Monument, in which no differences emerged across years (Figure 2). Not surprisingly, among all varieties, water limitation significantly reduced grain yield (−26 and −49% in I_M and I_L, respectively, compared to I_H restoration). The interaction I × C showed that Lewis and Santa Cruz obtained significantly higher yield than the other cultivars at I_H (2.99 t ha⁻¹ vs. 2.41 t ha⁻¹), and that the yields obtained for I_M were in line with those recorded at full water replenishment in all the remaining cultivars.

Table 1. Analysis of variance (P) of studied variables as affected by year (Y), water regime (I) and cultivar (C).

EFFECT	DF	Grain Yield	Pods Plant	1000 Seed Weight	Seed Pods	Plant Height	LAI	Harvest Index	WUE
Year (Y)	1	0.011	0.150	0.385	0.556	0.672	0.994	0.159	0.013
Water Regimes (I)	2	<0.001	<0.001	<0.001	0.109	<0.001	<0.001	0.132	<0.001
Cultivar (C)	4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001
Y × I	2	0.777	0.200	0.180	0.468	0.868	0.496	0.323	0.052
Y × C	4	0.005	0.719	0.161	0.767	0.748	0.282	0.074	0.114
I × C	8	0.002	<0.001	0.188	0.929	0.004	<0.001	0.008	0.469
Y × I × C	8	0.172	0.061	0.271	0.715	0.745	0.111	0.455	0.720

DF = degree of freedom; LAI: leaf area index; WUE: water use efficiency.

The number of pods per plant was influenced by irrigation regimes, cultivars and their interaction. Fully irrigated Lewis and Santa Cruz produced the highest number of pods per plant at ~74, which was significantly more than Matador and Monument (Figure 3).

The seed weight was significantly affected by cultivar and magnitude of irrigation. Lewis showed a significantly lower 1000-seed weight (29.8 g) vs. about 33 to 35 g for the other four cultivars. Averaged across year and cultivar, in the I_L treatment a lower 1000-seed weight was recorded (11% when compared with the fully irrigated treatment I_H, Figure 4).

Seed number per pod was influenced by cultivars (Figure 5) with a range of 6.3 seeds per pod (Lewis) to 7.4 (Monument). Neither year of cultivation nor irrigation significantly affected this parameter.

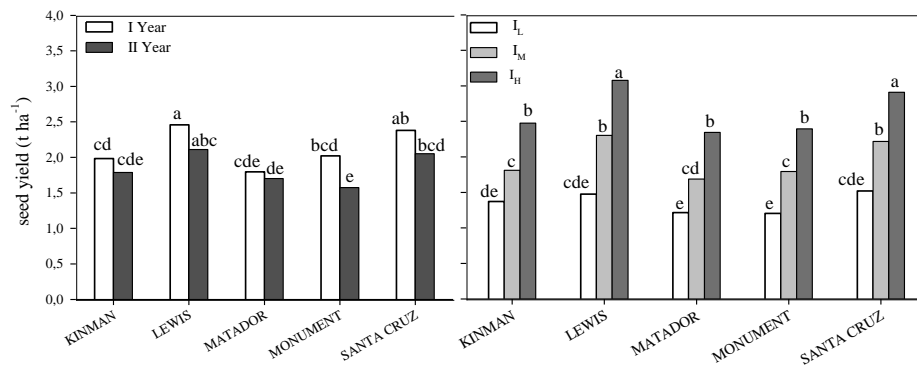


Figure 2. Seed yield (t ha⁻¹) among guar cultivars in the two years of the experiment, averaging water regimes (left), and in the three levels of irrigation, averaging the two-year results (right). Within each box, bars with different letters differ for $p < 0.05$.

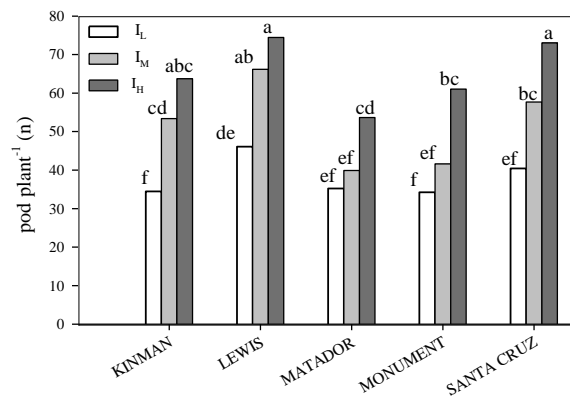


Figure 3. Two-year average number of pods per plant for each guar cultivar at three levels of irrigation. Bars with different letters differ for $p < 0.05$.

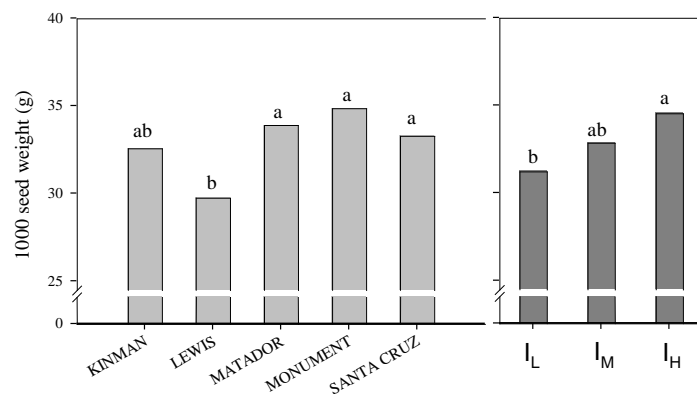


Figure 4. Two-year 1000-seed weight (left) of five guar cultivars across three water regimes and (right) two-year 1000 seed weight (right) of three irrigation levels among five guar cultivars, 2011–2012, Ispica, Italy. Bars with different letters differ for $p < 0.05$.

The significant interaction of plant height indicates that the five cultivars did not respond in the same way to irrigation (Table 1, Figure 6). The tallest plants were recorded in non-branching Monument at I_H (82.8 cm), which was significantly taller than at I_M. For the remaining cultivars, the irrigation treatments did not produce significant differences among the studied levels.

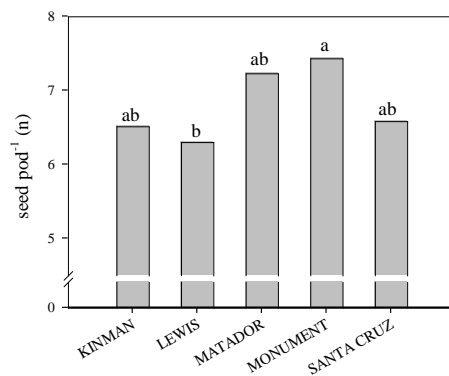


Figure 5. Two-year average seeds per pod among five guar cultivars averaged among three water regimes. Bars with different letters differ for $p < 0.05$.

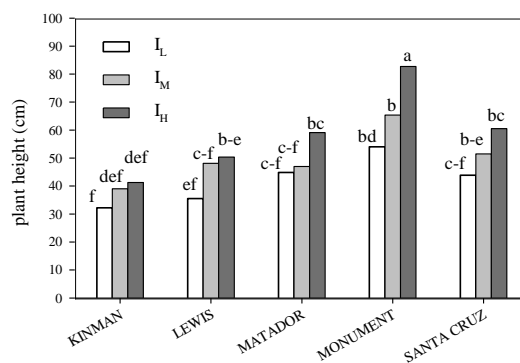


Figure 6. Two-year plant height (cm) across three levels of irrigation among five guar cultivars. Bars with different letters differ for $p < 0.05$.

The leaf area index (LAI) at the beginning of seed maturation followed the same pattern as plant height with a significant interaction of $I \times C$ (Table 1). Santa Cruz showed the highest LAI (4.6) when water was not a limiting factor (Figure 7). The lowest water availability significantly decreased LAI in all the cultivars compared to the optimal water supply. This was most pronounced for Santa Cruz, with an 84% LAI reduction from I_H to I_L . For Lewis, Matador and Kinman, LAI for I_M decreased by about 0.8 from I_H , although this was not significant. There was no change in LAI for Monument at I_H and L_M .

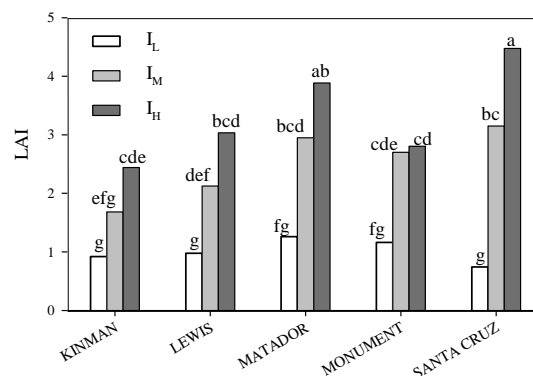


Figure 7. Leaf area index in response to three levels of irrigation among five guar cultivars over two years. Bars with different letters differ for $p < 0.05$.

The harvest index (HI) varied from 0.27 to 0.29 in 2011 and from 0.25 to 0.27 in 2012, and the effect of the level of irrigation imposed on HI was not relevant.

Correlation coefficient analyses indicated that seed yield was positively and highly correlated with pods per plant, plant height, LAI, and WUE ($p \leq 0.001$), and with 1000-seed weight ($p \leq 0.01$), whereas seed per pod and HI did not show any effect (Table 2).

Table 2. Correlation coefficients between seed yield and parameters. HI: harvest index.

	<i>r</i>	F	<i>p</i>
Pods Plant ⁻¹	0.924	511.050	0.000
1000 seed weight	0.247	5.723	0.019
Seeds Pod ⁻¹	0.010	0.009	0.924
Plant height	0.378	14.712	0.000
LAI	0.713	90.741	0.000
WUE	0.482	26.667	0.000
HI	0.029	0.072	0.790

3.2. Water Use Efficiency

The water use efficiency was affected by year, water regime and cultivar, but no interaction was determined (Table 1). The highest values of water use efficiency were in the first year (+34% than the value recorded in 2012, in which 0.93 kg m⁻³ of WUE was recorded) and in the water regimes I_L (1.44 kg m⁻³) with increments in water use efficiency of +34 and +95% when compared with I_M and I_H, respectively). Moreover, Lewis and Santa Cruz showed a +26% WUE when compared with the average of the Matador and Monument, reporting the lowest values (0.97 kg m⁻³) (Figure 8).

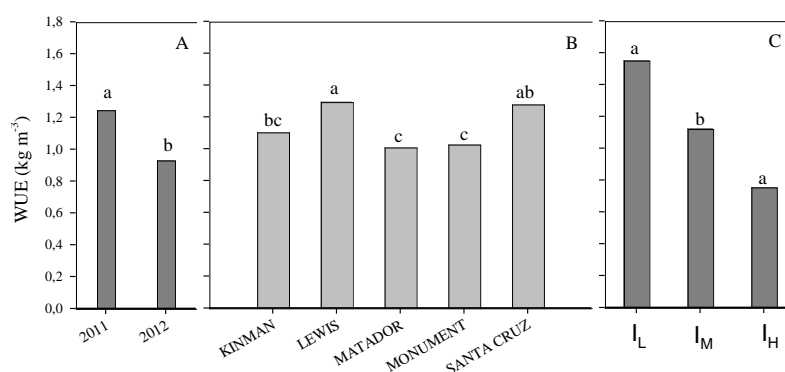


Figure 8. Two-year average water use efficiency (kg grain m⁻³) in guar (A) by year across five guar cultivars and three irrigation levels, (B) by guar cultivar across three irrigation levels, and (C) by irrigation level averaged for five guar cultivars. Within each box, bars with different letters differ for $p < 0.05$.

4. Discussion

Drought is one of the most important abiotic stress factors affecting crop productivity, especially in a semi-arid environment such as the one in which guar was tested in this work. The adoption of drought-tolerant species has been viewed as a long-term solution to stabilize yield under water-limited conditions. In this regard, guar has been introduced as a valuable crop in semi-arid areas [5] due to its low requirements of water supplies compared to other similar crops [23–25]. The grain yields reported in this study for I_H ranged from 2.09 to 3.28 t ha⁻¹ and were in agreement with a previous report from the same area [26] but higher than those reported by other authors [27–29] obtaining yield around 1.1 t ha⁻¹. In contrast, a greater variability was reported by Pathak [30] on 41 varieties grown in South India, but seed yield ranged from 0.5 to 2.8 t ha⁻¹, which was comparable to our results.

In relation to water stress, our findings confirm that guar achieves reasonable seed yield production even in water-limited conditions. Grain yield was greater at the full ET replacement (on average 2.64 t ha⁻¹), but the mean grain yield decrease was no greater than 49% when irrigation was reduced

by 75% from I_H to I_L . Deficit irrigation limited grain yield, but it proved to be a way to save 50% irrigation water (I_M) with a 26% grain yield reduction.

The cultivars showed different yield performance in response to water regimes. Lewis and Santa Cruz had higher seed yields than other cultivars at I_H and I_M . Lewis and Santa Cruz cultivars were the most productive varieties (2.5 t ha^{-1}) in a previous experiment in the same environment [24]. Singla et al. [28] reported that Lewis showed a higher grain yield and number of pods per plant than Kinman under drought conditions. Alexander et al. [18], in an irrigation trial on Kinman, Lewis and Santa Cruz cultivars, obtained lower yields when compared to our results; they also observed Lewis to be the most productive cultivar.

Stafford and McMichael [31] reported that the component of yield most affected by water stress was the number of pods per plant, while seed weight and seeds per pod had progressively smaller effects on seed yield. In contrast, in our experiment, all the yield components except seeds per pod were significantly affected by water stress.

Lewis and Santa Cruz showed the highest number of pods per plant—a parameter that has proved to be highly effective in determining seed yield. Correlation coefficient analyses revealed that pods per plant had a higher positive direct effect on seed yield than other variables ($r = 0.924^{***}$, Table 2). These findings are consistent with Gresta et al. [32] and Meftahizade et al. [27], who found a significantly positive correlation of pods per plant with seed yield. Moreover, to verify the effect of water regime on the number of pods, Meftahizade et al. [27] applied an irrigation management approach with water replenishment limited to specific phenological stages (sowing–flowering; sowing–flowering–seed formation; sowing–flowering–seed formation and prior to harvesting). As a result, they obtained a seasonal water balance ranging from 2000 to $4000 \text{ m}^{-3} \text{ ha}^{-1}$. This is comparable with the total water experienced in our experiment (1828 and $3570 \text{ m}^{-3} \text{ ha}^{-1}$ for I_M and I_H , respectively, averaging the year data) but dramatically different in terms of water availability during specific periods of the crop season. In particular, in the experiment conducted by Meftahizade, the absence of water restoration starting from flowering led to a drastic pods per plant reduction (-74%), whereas -21% was registered in our experiment.

Results of ANOVA analysis showed no effect of irrigation on the number of seeds per pod, which seems to respond only to genotypes. In contrast to our findings, Meftahizade et al. [33] reported a positive impact of irrigation on the number of seeds per pod and a significant positive correlation of plant height with seed yield.

The minimal variation observed in HI might result from the irrigation management. We determined a slight water stress during early guar growth, when critical reproductive organs are formed. In contrast, Ahmed et al. [34], similar to the results reported earlier by Meftahizade et al. [27], used a water distribution approach to irrigation management based on crop phenology that led to a severe reduction in soil water content during different stages of crop growth. Even though the author documented a recovery potential of guar, they also reported a significant reduction in harvest index as a result of the imposition of water stress during the reproductive phase—i.e., flowering formation—which is critical for guar.

The sensitivity to water stress during flower formation was confirmed by Baath et al. [35] in a lab experiment. There different day/night temperature regimes were imposed, and flower initiation suppression was observed under the higher temperature regimes ($36/28$ and $40/32 \text{ }^\circ\text{C}$). This evidence could also explain the yield reduction reported in our experiment in the warmer year (2012) when repeated temperature peaks (up to $39.7 \text{ }^\circ\text{C}$) were recorded and over 40 days with maximum day temperatures over $33 \text{ }^\circ\text{C}$ were experienced.

As concerns water use efficiency, the literature reports one guar study conducted in Sudan [34]. Their WUE values ($0.3\text{--}0.6 \text{ kg m}^{-3}$) were much lower than ours but with a comparable seed yield. It is possible that the total seasonal moisture (rainfall or irrigation) was much greater than in our Mediterranean region.

5. Conclusions

The findings of this study provide original information about the combined effect of irrigation regimes and cultivar on guar yield cultivated under drought conditions. The experiment contributes to improving our knowledge of the response of guar crops grown under limited irrigation.

The results demonstrated that Lewis and Santa Cruz showed significantly greater grain yields compared to the other cultivars both under fully watered and water-limited conditions.

The results demonstrate that guar has a high yield potential when irrigated at 100% soil water deficit replenishment. The results also suggest that imposing 50% of water deficit (I_M) may be a good strategy to increase crop water use efficiencies in low available water environments or when full irrigation is prevented by economic limitations. This attribute of guar likely demonstrates its ability to retain productivity under water-limiting conditions relative to other crops.

In conclusion, the differences which emerged when comparing our results with the few field experiments reported in the literature suggest productive advantages of irrigation strategies which aim to continuously restore even a limited amount of water, as long as an efficient water distribution system is present.

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