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Differential responses of two local and commercial guar cultivars for nutrient uptake and yield components under drought and biochar application

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Drought is one of the abiotic stresses that can reduce crop yields. It has a major impact on crop yield reduction. For crops under stress, organic modifiers such as biochar can be useful. Guar (*Cyamopsis tetragonoloba* L.), an annual legume from the *Fabaceae* Family, is highly adaptable to arid and semi-arid regions, with many applications in various industries. Field experiments were carried out in a randomized complete block design with three replications using a split-split plots arrangement. The aim was to evaluate the influence of irrigation levels (Ir1 = 10, Ir2 = 14, and Ir3 = 17 days irrigation cycle) and biochar (B1 = 0, B2 = 5, and B3 = 10 tons ha^{-1}) application on physiological traits [(chlorophyll a and b, chlorophyll index (SPAD), relative leaf water content (RWC), electrolyte leakage (EL), canopy temperature, leaf area, water use efficiency (WUE)], morphological parameters (length and diameter of the stem, pod length, fresh weight of root and plant, root length), yield components (seed yield, number of branch plant^{-1}, number of clusters plant^{-1}, pod plant^{-1}, seed pod^{-1}, seed plant^{-1}, 1000-seed weight, and gum contents), and leaf nutrient uptake (Ca, Mg, P, Na, and K) of two commercial and local cultivars (cv1 = RGC-936 and cv2 = Saravan) of the guar plant. It was observed that the Ir3 irrigation treatment produced the highest seed yield (1921.8 kg ha^{-1}) in terms of water stress. However, the maximum pod plant^{-1} (75.5), seed plant^{-1} (454.2), seed yield (1871.1 kg ha^{-1}), leaf area (861.8 mm^2), SPAD (92.2), Mg (49.8 mg g^{-1}), Na (43.3 mg g^{-1}) and P (0.49 mg g^{-1}) were observed in RGC-936. The results also revealed that biochar was more effective than cultivars in terms of morphological traits. While yield and yield components were affected by cultivar, irrigation at different levels also had a significant effect on functional traits, physiology, and morphology. The addition of biochar appeared to have a positive effect on water stress alleviation and guar growth and leaf nutrient uptake. According to Pearson's correlation analysis, plant weight and length, root weight and length, stem diameter, seed pod^{-1}, branches plant^{-1}, and 1000-seed weight are moderately correlated with seed yield, while pod plant^{-1} and seed plant^{-1} are strongly associated with seed yield. On the other hand, the pod length, branches plant^{-1}, and gum content showed a positive but not significant relationship.

Keywords Soil amendment, Gum content, Nutrient uptake, Seed yield, PCA, Guar

Drought is a common environmental stress that limits production in the agricultural sector worldwide[1]. Due to various droughts, reduction in atmospheric precipitation, excessive use of groundwater, and increase in water consumption, optimal irrigation management is necessary in this sector[2]. To achieve this, low water demand plants such as medicinal-industrial crops with a short growing season and low-water demand should

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be identified and replaced by industrial medicinal plants adapted to the climate of the region. In addition, agricultural practices should be implemented to maximize the use of available resources, especially soil and water[3–5]. The presence of extensive root systems in medicinal plants indicates their adaptability to reduced access to water and nutrients[6]. Planting these plants can be effective in increasing the productivity of water and soil resources due to their low water requirements, high potential for drought tolerance, and ability to produce in marginal and low-yielding lands while meeting the economic needs of villagers and various pharmaceutical and food industries[7].

Arid regions have a shortage of vegetation, which results in soil that lacks organic matter. Organic matter is important for soil fertility, improving soil physical and chemical properties, and increasing crop yields, particularly in hot regions. Several studies[8–10] have confirmed this. Biochar is a solution for reducing carbon dioxide emissions and a rich source of carbon. It is made by pyrolyzing plant residues in an oxygen-deficient or oxygen-free environment[11]. Biochar can remain in soil for hundreds or even thousands of years, depending on how it was created. Biochar offers several benefits, including reducing the volume of waste materials, producing energy[12], increasing the nutritional value of residues, and increasing the cation exchange capacity of soil[13].

Guar (*Cyamopsis tetragonoloba* L.) is a legume that grows during the summer season. It is highly tolerant to drought and can adapt well to poor soil conditions. Guar requires ample sunlight and low relative humidity during the growing season, but needs only a little surface water[14–16]. Guar gum, a derivative of Guar, has a wide range of applications in industries such as processed foods, oil and gas drilling, mining, and paper manufacturing. Guar gum is used as a thickening and stabilizing agent in processed foods[15,17–19]. Additionally, tender green guar is a significant food source in southeastern Iran[20]. The performance of guar is influenced by various factors such as water stress, soil fertility, crop variety, climate, and plant protection. These factors play an important role in enhancing its potential under specific agro-climatic conditions[21,22].

Numerous studies have focused on the use of biochar in crops under drought stress, including *Solanum lycopersicum*[23], *Zea mays*[24], *Cicer arietinum*[25], *Triticum aestivum*[26], *Abelmoschus esculentus*[27], *Glycine max*[28], *Laptochloa fusca*[29], and *Gossypium arboreum*, and *Oryza sativa*[30]. However, studies on how biochar, as a low-quality soil modifier, affects guar under drought stress, particularly between native and commercial varieties, are limited. Prior research has evaluated the effects of bio-fertilizers (mycorrhiza and rhizobium) on morphological and yield traits of guar under drought stress conditions[31]. Additionally, studies have examined the growth of guar genotypes under different irrigation regimes and biogenic silica supplementation in the arid southwest of the USA[22], and the use of ascorbic acid and calcium carbonate to mitigate the effects of drought stress on guar[32].

Previous research on guar has mostly focused on the planting date of its different genotypes or different irrigation regimes. However, in arid and semi-arid areas where water scarcity and low soil quality are common problems, studying the impact of soil modifiers under drought stress could improve the crop's performance. Considering the hot and dry weather conditions in Yazd province, particularly in Ardakan city, and the need for cultivating low water-demanding and industrial medicinal plants, we chose to examine the effects of drought stress and biochar as a soil amendment on physiological and morphological traits, yield components, and leaf nutrient uptake of two local and commercial cultivars.

Materials and methods

Field experiment

This research was conducted in July, 2021 in the research farm of Ardakan University, Yazd Province, Iran (22°20'N, 53°48'E; 1035 m above sea level) with an average annual rainfall of 65 mm, average annual temperature of 19 °C, an absolute maximum and minimum temperature 47 and − 14 °C respectively, a maximum daily rainfall 28.5 mm and an average relative humidity of 34% (Fig. 1) in the form of a split split-plot arrangement in a randomized complete block design with three replications. Two commercial and local cultivars RGC-936 (cv1) and Saravan (cv2) were supplied by the Research Institute of Medicinal and Industrial Plants, Ardakan University, Yazd. The seeds are sown in mid-July after plowing, disking, bed preparation, and mixing different levels of biochar (made from walnut and almond shells) with surface soil (0 to 10 cm) in plots of 12 m^2 (length × width, 3 × 4 m). To make biochar, the hard shell of walnut and almond is first washed well with water and dried at room temperature for 48 h, then placed in an oven at 105 °C for 24 h to remove the remaining moisture. The almonds are then ground and standard sieves are used to separate particles between 0.5 and 1 mm, then was placed in an electric furnace under inert nitrogen gas and the temperature of the furnace was increased at a rate of 10 °C/min to 400 °C to prepare biochar. Then, it was kept at 400 °C for 120 min to pyrolysis the residue well. Then, nitrogen gas was applied to bring the furnace temperature to the ambient temperature[33]. Three irrigation treatments were applied: 10 (Ir1), 14 (Ir2), and 17 (Ir3) days irrigation cycle. Three levels of biochar 0 (B1), 5 (B2), and 10 (B3) t ha^{-1} were also used. Irrigation treatments were carried out in the main plot and guar cultivars were in the sub-plot the biochar was determined to the sub-sub plot. No other fertilizer was applied to the soil during the planting process, as rotten animal manure was applied to the soil before planting. However, 60 kg ha^{-1} of nitrate was applied as ammonium nitrate (NH_4NO_3) after the fourth and eighth leaf emergence, as a lack of nodule formation can appear while growing. Soil samples were taken from a depth of 0 to 40 cm to determine the weight moisture content of the field capacity and permanent wilting to be 27.3 and 9% respectively using a pressure plate in the laboratory. Irrigation water was applied by the flooding method to simulate farming practices in the study area. Irrigation treatments were applied in September at the same time as the third irrigation and after full plant establishment, when the plants reached the four or five leaf stage. As shown in Fig. 1, the rainfall during the growing season of guar in the study area during the summer season was only 1 mm, which could be ignored to consider the effective rainfall when estimating the water requirements of the plant. Soil samples and soil moisture measurements were taken before each irrigation. The depth of water that should have been applied to each plot, was the difference between the soil moisture and the previously measured field capacity moisture.

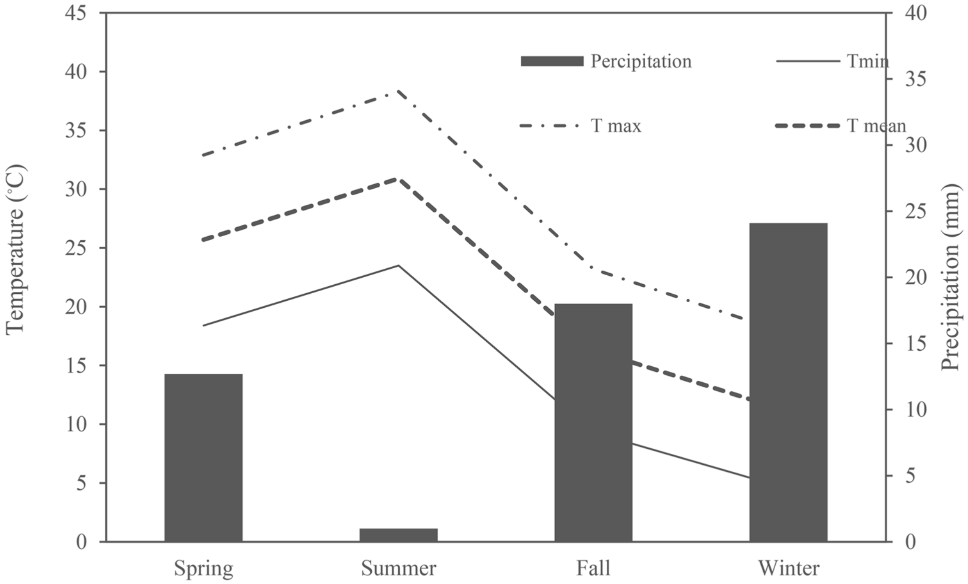

Figure 1. Seasonal changes of temperature and precipitation parameters in the study area (Ardakan, Iran).

(A) Physical characteristics					
Texture	$CaCO_3$ (%)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})
Loam	20.4	17	36	47	1.49

(B) Chemical characteristics											
EC	pH	C	N	P	K	HCO_3^-	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	
(dS m^{-1})		(%)	(%)	(mg l^{-1})		(meq l^{-1})					
5.7	7.7	0.98	0.085	69.7	891	3.9	809.1	88.7	136.0	726.6	Soil
1.35	8.5	52.2	-	40.5	425.5	-	-	1.6	1.1	-	Biochar

Table 1. Physical and chemical characteristics of the experimental field soil and biochar.

The amount of water required for irrigation of each plot was determined using Eq. (1), which estimates the amount of water required to compensate for the lack of soil moisture (θ_{soil}) up to the capacity of the field (θ_{FC}):

$$\text{Irrigation Depth} = (\theta_{\text{FC}} - \theta_{\text{soil}}) \times \text{Rd} \tag{1}$$

Where Rd is the root depth. Finally, the irrigation requirement for each plot was calculated as follows:

$$\text{Irrigation Volume} = \text{Depth of irrigation} \times \text{Plot area} \times \text{Number of irrigation} + \text{Effective rainfall} \tag{2}$$

At the beginning of each plot there was a volume meter, which was used to water the plots. The average amount of water used for the 10-day (5 irrigations during the growing season), 14-day (4 irrigations), and 17-day (4 irrigations) cycles was calculated to be 171, 135, and 109 L m^{-2}, respectively. Table 1 shows some of the physical and chemical characteristics of the soil and biochar.

Yield components, physiological and morphological characteristics

When most pods are brown (Gresta et al., 2018), the guar plant is considered mature. Harvesting was carried out at 80% of maturity (late October to early November) in different cultivars. Data for various parameters were collected from 10 randomly selected plants from each plot, taking into account the deletion of data from the border region. Subsequently, guar plants were carefully uprooted by hand to record physiological and morphological characteristics, yield components, and leaf nutrient uptake. Accordingly, the number of branch plant^{-1}, number of clusters plant^{-1}, pod plant^{-1}, seed pod^{-1},1000-seed weight, canopy temperature, leaf surface, length and diameter stem, pod length, fresh weight of root and plant, root length and gum contents was also measured. The temperature of the canopy was measured with an infrared thermometer (model INFRARED DT-8550) at a specific time (11 A.M.) facing the green cover. Sabahelkheir et al.,[34] method was used for gum separation. At the end of the period, the reading of the Soil Plant Analysis Development (SPAD) was done in the leaves; Chlorophyll a and b were measured by Arnon[35]; relative leaf water content (RWC) was checked by Ritchie et al., (1990); electrolyte leakage (EL) was also done by applying the method developed by Blum and Ebercon[36]. Water use efficiency (WUE) for irrigation, was calculated as follows:

$$\mathrm{WUE} = \frac{\text{Yield of the guar (kg ha} - 1)}{\text{Water applied (mm)} + \text{Effective rainfall (mm)}} \tag{3}$$

Whereas, water applied= [(No. of irrigation× depth of irrigation)] + Effective rainfall (mm).

Leaf nutrient uptake

Several fully developed leaves from each treatment and replicate were selected to measure leaf mineral content. Leaf samples were washed with distilled water, oven dried at 70 °C for 48 h, ashed and digested in 1 M HCl. Samples were then ready for measurement[37]. Flame photometry[38] was used to determine the phosphorus (P) concentrations of the samples. The titration method[38] was also used to determine Sodium (Na), Potassium (K), Calcium (Ca), and Magnesium (Mg).

Data analysis

We conducted a 3-way ANOVA to test for significant differences between the means of the applied treatments. Afterwards, we performed a post hoc Duncan's test at the 5% probability level in the SPSS package version 23.0 for Windows. The field experiments were carried out using a split split-plots arrangement in randomized complete block design with three replications. Irrigation treatments were applied in the main plot and guar cultivars were in the sub-plot. The biochar was determined in the sub-sub plot. Additionally, we used Pearson's correlation analysis and principal component analysis (PCA) with varimax rotation and Kaiser normalization to determine the relationship between the characteristics.

Results and discussion

Supplementary Tables 1 and 2 exhibit the results of the analysis of variance (ANOVA) conducted on the impact of various experimental treatments on the yield and yield components, physiological and morphological traits in two guar cultivars. The ANOVA revealed that some of the traits of the both cultivars such as plant height, root length, plant weight, root weight, stem diameter, number of branches plant^{-1}, number of pod plant^{-1}, number of seed pod^{-1}, number of clusters plant^{-1}, seed plant^{-1}, 1000-seed weight, seed yield, gum contents, RWC, EL, SPAD, canopy temperature, leaf surface, and chlorophyll a content were significantly ($p < 0.05$) affected by the experimental factors and/or their two-way interactions. However, no significant ($p > 0.05$) changes were observed for pod length and chlorophyll b value of guar cultivars upon the employed treatments. Furthermore, the three-way interaction between guar cultivars, irrigation treatment, and biochar amendment did not have a significant impact on any of the traits tested. Tables 2, 3, 4 and 5 show simple means for the measured characteristics that were statistically significant ($p < 0.05$), while Tables 6 and 7, and Fig. 2 explain the interaction means of the significant ($p < 0.05$) characteristics.

Simple effect of irrigation treatments

The ANOVA results showed that irrigation treatments had a significant impact on the yield and yield components of guar cultivars. Seed yield, the number of branches plant^{-1}, the number of pods plant^{-1}, and the number of seeds plant^{-1} were all affected by the irrigation treatments (Table 2). All traits, except gum content, 1000-seed weight, and branches plant^{-1}, were highest in the Ir3 treatment, which had a 17-day irrigation cycle. Alexander et al.[39] also reported that guar requires relatively little water to grow. Gum content did not differ significantly between the control and the 14-day irrigation cycle treatment, but the 17-day irrigation cycle resulted in a 24% decrease in gum percentage compared to the control. The 10-day irrigation treatment produced the highest gum content at 33.4%, which is an important metric for the use of guar seed in various industries[40]. The percentage of guar gum was only affected by the irrigation treatment (Supplementary Table 1).

There was no significant difference between the different treatments in terms of cluster plant^{-1}, pod length, root length, and chlorophyll b content. Drought and salinity are major abiotic stresses that negatively impact crop yield according to the various studies [5,41–43]. Guar, being drought-tolerant, is capable of recovering and maintaining adequate seed yield and dry matter under stress. As a result, the best result for yield traits was obtained in the irrigation treatment Ir3, which included seed yield, pod plant^{-1}, seed pod^{-1}, and seed plant^{-1}. In terms of morphological characteristics such as stem diameter, root weight, plant weight, and plant height, the guar plant was subjected to water stress, and the highest values were obtained in plants irrigated by treatment Ir1 (Table 3). This indicates that the guar plant alters its morphological characteristics to cope with drought stress and produce more energy to improve functional traits and seed production.

Irrigation	Gum content (%)	Seed yield (kg ha^{-1})	1000-seed weight (g)	Branches plant^{-1} (No.)	Pod plant^{-1} (No.)	Seed pot^{-1} (No.)	Seed plant^{-1} (No.)
Ir1	33.4^{a} ± 1.5	1758.5^{b} ± 12	49.3^{a} ± 2.1	4.9^{a} ± 0.8	66.3^{b} ± 2.4	5.3^{b} ± 0.1	356.7^{c} ± 8.9
Ir2	31.2^{a} ± 1.2	1675.0^{c} ± 15	42.6^{b} ± 1.8	3.7^{ab} ± 0.5	63.9^{b} ± 2.1	6.0^{a} ± 0.4	393.2^{b} ± 11.4
Ir3	25.3^{b} ± 1.1	1921.8^{a} ± 23	43.1^{b} ± 1.3	3.0^{b} ± 0.2	70.9^{a} ± 1.5	6.2^{a} ± 0.6	445.9^{a} ± 12.7

Table 2. Mean comparison of single effect of irrigation treatment on yield and yield components of guar. Each mean values followed by the same letters are not significantly different for $p \leq 0.05$ according to the Duncan's test. Data are means ± standard error of three replicates.

Irrigation	SPAD	Cl. a (mg g^{-1})	EL (%)	RWC (%)	WUE (kg m^{-3})	Tem ($^\circ$C)	Stem diameter (mm)	Leaf area (mm^2)	Root weight (g)	Plant Weight (g)	Plant height (cm)	Mg (mg g^{-1})	Ca (mg g^{-1})	K (mg g^{-1})	Na (mg g^{-1})	*P* (mg g^{-1})
Ir1	$83.7^{b} \pm 2.3$	$1.2^{b} \pm 0.1$	$33.1^{c} \pm 1.7$	$0.78^{a} \pm 0.03$	$0.05^{c} \pm 0.01$	$33.8^{c} \pm 1.2$	$6.9^{a} \pm 0.4$	$793.2^{b} \pm 12.1$	$3.47^{a} \pm 0.2$	$67.4^{a} \pm 2.8$	$57.2^{a} \pm 1.0$	$45.8^{b} \pm 1.8$	$12.4^{b} \pm 0.2$	$18.6^{c} \pm 1.1$	$28.9^{c} \pm 0.7$	$0.43^{b} \pm 0.02$
Ir2	$98.5^{a} \pm 3.1$	$1.5^{a} \pm 0.1$	$40.9^{b} \pm 1.5$	$0.75^{a} \pm 0.04$	$0.07^{b} \pm 0.01$	$35.7^{b} \pm 1.1$	$6.8^{a} \pm 0.2$	$890.4^{a} \pm 19.3$	$3.4^{a} \pm 0.1$	$73.9^{a} \pm 3.2$	$57.3^{a} \pm 0.9$	$56.3^{a} \pm 2.5$	$11.9^{b} \pm 0.1$	$35.8^{b} \pm 1.5$	$50.6^{a} \pm 2.1$	$0.51^{a} \pm 0.05$
Ir3	$87.4^{b} \pm 2.2$	$1.0^{b} \pm 0.1$	$46.2^{a} \pm 2.3$	$0.28^{b} \pm 0.01$	$0.08^{a} \pm 0.01$	$37.5^{a} \pm 1.4$	$5.9^{b} \pm 0.2$	$775.4^{b} \pm 10.8$	$2.6^{b} \pm 0.1$	$44.9^{b} \pm 1.6$	$46.5^{b} \pm 0.7$	$42.1^{c} \pm 1.2$	$17.9^{a} \pm 0.4$	$67.3^{a} \pm 1.7$	$40.9^{b} \pm 1.6$	$0.45^{b} \pm 0.03$

Table 3. Mean comparisons of single effects of irrigation treatment on physiological, morphological traits and leaf nutrient uptake. Each mean values followed by the same letters are not significantly different for $p \leq 0.05$ according to the Duncan's test. Data are means ± standard error of three replicates.

Cultivar	SPAD	Leaf area (m^2)	Plant Weight (g)	Branches Plant^{-1} (No.)	Pod plant^{-1} (No.)	Seed plant^{-1} (No.)	Seed yield (kg ha^{-1})	1000-seed weight (g)	Mg (mg g^{-1})	Ca (mg g^{-1})	K (mg g^{-1})	Na (mg g^{-1})	*P* (mg g^{-1})
RGC-936	92.2^a ±3.1	861.8^a ±11.2	56.2^a ±1.3	0.0^b ±0.0	75.5^a ±2.01	454.2^a ±12.5	1871.1^a ±26.2	41.2^b ±1.5	49.8^a ±2.6	12.4^b ±0.8	38.4^a ±1.7	43.3^a ±3.5	0.49^a ±0.02
Saravan	87.5^a ±2.2	777.5^b ±9.4	67.9^a ±2.5	7.7^a ±0.05	58.5^b ±1.07	343.0^b ±8.3	1677.3^b ±23.1	48.9^a ±1.7	46.4^a ±2.2	15.9^a ±1.4	42.7^a ±2.5	37.1^a ±3.0	0.43^b ±0.01

Table 4. Mean comparison of single effect of cultivars guar on some measured traits. Each mean values followed by the same letters are not significantly different for $p \leq 0.05$ according to the Duncan's test. Data are means ± standard error of three replicates.

Biochar	SPAD	EL (%)	Plant weight (g)	Root weight (g)	Plant height (cm)	Root length (cm)	Leaf area (mm^2)	Mg (mg g^{-1})	Ca (mg g^{-1})	K (mg g^{-1})	Na (mg g^{-1})	*P* (mg g^{-1})
B1	85.2^{c} ±1.0	36.9^{c} ±0.8	49.9^{b} ±2.3	2.8^{b} ±0.2	48.7^{c} ±2.1	18.5^{b} ±0.6	725.4^{c} ±10.7	44.8^{c} ±0.3	12.9^{b} ±0.5	31.4^{c} ±1.1	31.6^{c} ±0.6	0.43^{c} ±0.02
B2	89.2^{b} ±1.2	39.7^{b} ±0.5	53.9^{b} ±2.5	2.9^{b} ±0.3	52.4^{b} ±1.6	19.7^{ab} ±1.4	819.7^{b} ±11.2	48.1^{b} ±0.7	12.1^{b} ±0.3	40.8^{b} ±1.5	40.1^{b} ±0.5	0.47^{b} ±0.01
B3	95.2^{a} ±1.6	43.6^{a} ±0.4	82.6^{a} ±2.8	3.8^{a} ±0.3	59.6^{a} ±2.5	21.7^{a} ±1.2	913.9^{a} ±14.6	51.4^{a} ±0.5	17.4^{a} ±0.8	49.6^{a} ±2.3	48.7^{a} ±0.8	0.50^{a} ±0.01

Table 5. Mean comparison of single effect of biochar on some measured traits. Each mean values followed by the same letters are not significantly different for $p \le 0.05$ according to the Duncan's test. Data are means ± standard error of three replicates.

Cultivar	Irrigation	K (mg g^{-1})	SPAD	Branches plant^{-1} (No.)	Pod plant^{-1} (No.)	clusters plant^{-1} (No.)	1000-seed weight (g)
RGC-936	Ir1	$17.5^{e} \pm 0.2$	$85.4^{cd} \pm 2.4$	$0.0^{c} \pm 0.0$	$74.0^{b} \pm 1.1$	$13.9^{a} \pm 0.6$	$49.7^{ab} \pm 1.4$
	Ir2	$34.1^{d} \pm 0.5$	$101.4^{a} \pm 2.1$	$0.0^{c} \pm 0.0$	$74.6^{b} \pm 1.7$	$14.4^{a} \pm 1.2$	$39.1^{c} \pm 1.0$
	Ir3	$63.6^{b} \pm 1.1$	$89.9^{c} \pm 1.8$	$0.0^{c} \pm 0.0$	$78.0^{a} \pm 1.3$	$9.6^{a} \pm 0.5$	$34.7^{d} \pm 1.1$
Saravan	Ir1	$20.0^{e} \pm 0.2$	$82.2^{d} \pm 1.7$	$9.8^{a} \pm 0.2$	$58.6^{c} \pm 1.9$	$13.4^{a} \pm 0.7$	$48.9^{ab} \pm 1.3$
	Ir2	$37.4^{c} \pm 0.7$	$95.5^{b} \pm 1.8$	$7.4^{b} \pm 0.2$	$53.3^{d} \pm 1.4$	$12.3^{a} \pm 0.4$	$46.2^{b} \pm 1.1$
	Ir3	$71.0^{a} \pm 1.3$	$84.8^{d} \pm 1.1$	$6.0^{b} \pm 0.1$	$63.8^{c} \pm 2.1$	$13.7^{a} \pm 1.1$	$51.5^{a} \pm 2.8$

Table 6. Mean comparisons of interaction effects of guar cultivars and irrigation levels on some measured traits. Each mean values followed by the same letters are not significantly different for $p \leq 0.05$ according to the Duncan's test. Data are means ± standard error of three replicates.

Irrigation	Biochar	Chlorophyll a (mg g^{-1})	K (mg g^{-1})	Na (mg g^{-1})	SPAD	Root weight (g)	Plant weight (g)	Plant height (cm)	Clusters plant^{-1} (No.)
Ir1	B1	$1.0^{bc} \pm 0.16$	$14.1^{g} \pm 1.7$	$17.8^{f} \pm 1.0$	$80.5^{d} \pm 1.3$	$4.0^{ab} \pm 0.6$	$66.2^{bc} \pm 4.0$	$51.5^{cd} \pm 3.9$	$13.7^{ab} \pm 2.3$
	B2	$1.2^{bc} \pm 0.13$	$17.8^{g} \pm 1.9$	$29.3^{e} \pm 1.2$	$82.1^{d} \pm 1.2$	$3.1^{bc} \pm 0.5$	$60.0^{cd} \pm 2.4$	$57.5^{bc} \pm 3.1$	$12.7^{ab} \pm 1.9$
	B3	$1.3^{ab} \pm 0.17$	$24.0^{f} \pm 1.7$	$39.6^{d} \pm 1.4$	$88.2^{c} \pm 1.7$	$3.3^{bc} \pm 0.5$	$75.6^{b} \pm 3.1$	$62.5^{ab} \pm 3.3$	$14.7^{ab} \pm 2.4$
Ir2	B1	$1.7^{a} \pm 0.31$	$27.6^{f} \pm 2.2$	$40.4^{d} \pm 1.5$	$95.2a^{b} \pm 1.5$	$2.2^{c} \pm 0.6$	$46.0^{de} \pm 5.6$	$50.3^{cd} \pm 3.5$	$12.8^{ab} \pm 2.2$
	B2	$1.1^{bc} \pm 0.11$	$36.5^{e} \pm 1.5$	$50.9^{b} \pm 2.3$	$97.8^{b} \pm 1.8$	$2.8^{bc} \pm 0.4$	$56.8^{cd} \pm 5.9$	$53.3^{cd} \pm 2.8$	$11.0^{ab} \pm 2.6$
	B3	$1.7^{a} \pm 0.32$	$43.2^{d} \pm 1.9$	$60.6^{a} \pm 2.8$	$102.4^{a} \pm 2.3$	$5.1^{a} \pm 0.7$	$118.8^{a} \pm 7.3$	$67.8^{a} \pm 3.5$	$16.5^{a} \pm 2.5$
Ir3	B1	$1.2^{bc} \pm 0.15$	$52.5^{c} \pm 2.4$	$36.7^{d} \pm 2.6$	$79.3^{d} \pm 1.8$	$2.1^{c} \pm 0.2$	$37.0^{f} \pm 2.5$	$44.4^{d} \pm 2.3$	$12.6^{ab} \pm 2.5$
	B2	$0.9^{bc} \pm 0.14$	$68.0^{b} \pm 3.2$	$40.1^{d} \pm 1.5$	$87.8^{c} \pm 1.9$	$2.6^{bc} \pm 0.4$	$44.3d^{e} \pm 3.7$	$46.5^{d} \pm 3.1$	$12.8^{ab} \pm 2.4$
	B3	$0.8^{c} \pm 0.11$	$81.4^{a} \pm 3.7$	$46.1^{c} \pm 1.8$	$94.9^{b} \pm 2.5$	$3.1^{bc} \pm 0.4$	$53.0^{cde} \pm 6.4$	$48.7^{cd} \pm 2.7$	$9.3^{b} \pm 3.3$

Table 7. Mean comparisons of interaction effects of irrigation levels and biochar on some measured traits. Each mean values followed by the same letters are not significantly different for $p \leq 0.05$ according to the Duncan's test. Data are means ± standard error of three replicates.

Table 3 demonstrates significant findings on how different irrigation levels affected the physiological properties of guar cultivars. Plants irrigated with Ir1 treatment had the maximum electrolyte leakage (EL) index, water use efficiency (WUE), and temperature (by 39%, 60%, and 11%, respectively) compared to those irrigated with Ir3. The results also showed that EL increased as the irrigation cycle increased, with the highest level of water stress. The stress-induced EL is usually accompanied by accumulation of reactive oxygen species (ROS) such as hydroxyl radicals, hydrogen peroxide, and superoxide radicals under stressful conditions. These compounds cause damage to the cell membrane and lead to the leakage of cell electrolytes, as explained in previous studies by Hernández et al.[44] and Soltani-Gerdefaramarzi et al.[5].

Water use efficiency (WUE) increases significantly with decreasing water consumption compared to the control, up to a 17-day irrigation cycle. When plants experience drought stress, they rely on the water stored in the soil, which not only reduces water consumption but also leads to an increase in water efficiency. Tabatabaei et al.[45] demonstrated that deficit irrigation has a significant positive effect on WUE. As the amount of irrigation water decreases, the relative leaf water content (RWC) also decreases (Table 3). These findings are consistent with previous studies by Akhtar et al.[23], Demir and Sahin[46], and Soltani-Gerdefaramarzi et al.[2], which showed that increased water stress can reduce leaf RWC by decreasing plant cell and tissue water uptake. When water stress is severe, it can severely damage the cell membrane, reducing the cell's ability to control cell membrane entry and exit[23].

According to Table 3, there was no significant difference in the amount of SPAD between the control treatment and the 17-day irrigation period. However, the 14-day irrigation period resulted in an increase in this parameter compared to the control. This increase suggests that the chlorophyll pigments in guar are somewhat resistant to moisture stress, as mentioned by Schütz and Fangmeier[47]. The findings presented in Table 3 indicate that the 14-day irrigation period decreased the content of chlorophyll a compared to the control, although there was no significant difference between the control treatment and the 17-day irrigation period. This result aligns with the findings of previous studies[2,48,49]. The decrease of chlorophyll a under moisture stress conditions is a clear indication of photo-oxidation of pigments and chlorophyll degradation[50]. Moreover, the mean comparison results showed that the temperature of the canopy increases with an increase in irrigation frequency (Table 3). This aligns with the findings of previous research conducted on barley[51] and pot marigolds[52], which showed that leaf temperature increased with the increase in irrigation frequency. Bahador et al.[53] also found that drought stress increased the vegetative temperature in cannabis plants. When soil water potential decreases under drought stress, responses such as increased stomatal resistance, decreased stomatal conductance, and even complete stomatal closure to prevent transpiration occur. This closure of stomata and reduction of transpiration leads to increased leaf temperature[54].

According to our findings, using reduced irrigation can significantly decrease the size of leaves. This reduction is due to the sensitivity of cell behavior to water deficit, as stated by[2]. This response may be caused by a signal

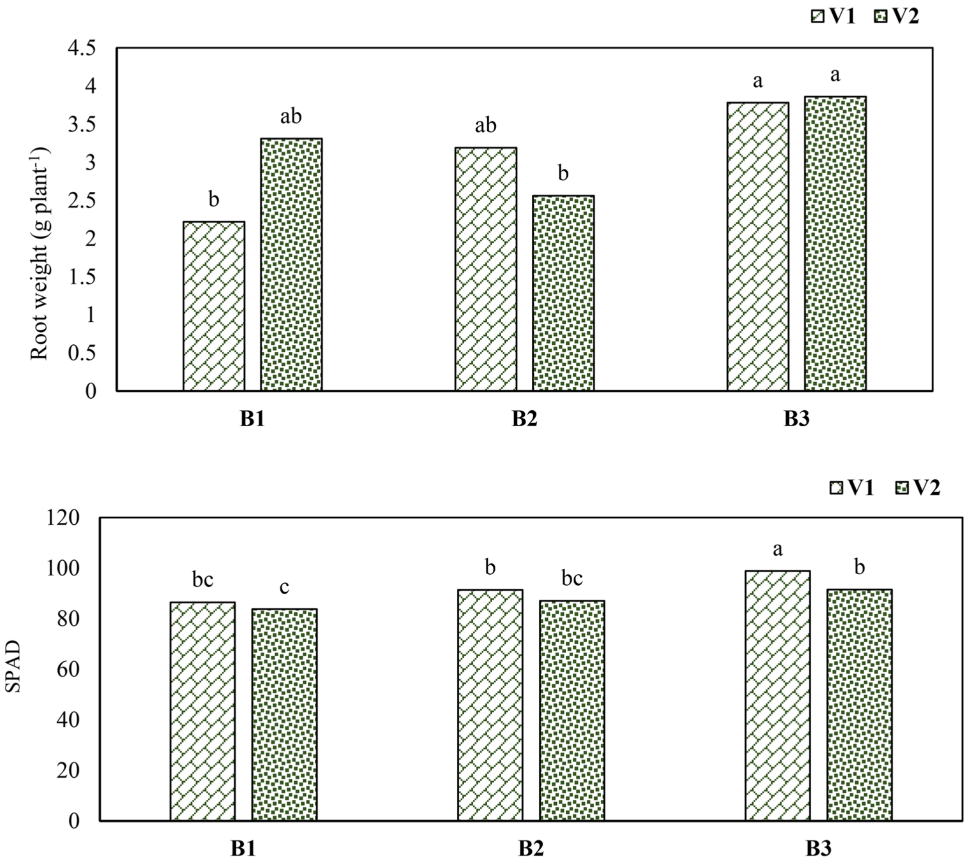

Figure 2. Mean comparisons of interaction effects of guar cultivars and biochar on SPAD and root weight. (Each mean values followed by the same letters are not significantly different for $P \leq 0.05$ according to the Duncan's test).

transmitted from the roots to the shoots, instructing them to limit leaf growth and ultimately close leaf stomata, as explained by Tabatabaei et al.[45].

As indicated in Table 3, different levels of irrigation treatments had significant impact on the nutrient concentrations of the leaves. The highest levels of Na and P in the leaves were observed when the plants were irrigated using a 14-day irrigation cycle. The concentration of Ca and K in the leaves increased (by 44% and 261%, respectively) with an increase in the irrigation cycle, while the concentration of Mg decreased. This increase in K concentration is believed to occur due to the role of this element in osmotic regulation and stomatal control[55] as a response to increasing stress.

Simple effect of cultivar types

Based on the findings in Table 4, the different cultivars had a significant impact on almost all yield traits except for the cluster plant^{-1}, seed pod^{-1}, and gum content. The Saravan cultivar showed the highest plant weight (67.9 gr), 1000-seed weight (48.9 gr), Ca (15.9 mg g^{-1}), K (42.7 mg g^{-1}), and branches plant^{-1} (7.7), while RGC-936 did not have any branches plant^{-1} (0.0). On the other hand, RGC-936 had the highest pod plant^{-1} (75.5), seed plant^{-1} (454.2), seed yield (1871.1 kgha^{-1}), SPAD (92.2), leaf area (861.8 mm^2), Mg (49.8 mg g^{-1}), Na (43.3 mg g^{-1}), and P (0.49 mg g^{-1}) (Table 4). Although the weight of 1000-seeds is mainly influenced by the amount of photosynthetic material, the number of seeds, and the capacity of each seed, it's important to note that the genotype and weather conditions during the plant's growth period also have an effect. It's worth mentioning that the cultivar did not significantly affect the physiological and morphological characteristics, except in a few cases like SPAD, leaf area, and plant weight. Based on Duncan's test, there was no significant difference at the 5% level between the mean values of SPAD and plant weight in two different cultivars. However, leaf area showed a significant difference of about 11% in the RGC-936 among the morphological traits. Comparison of the mean simple effects of the type of cultivar revealed no significant difference in the concentration of Mg, K, and Na elements between the two cultivars. On the other hand, the concentration of Ca was 28.46% higher in the RGC-936 compared to the Saravan type, while the opposite was observed in the case of P, with a 14% difference. In a study conducted in Iranshahr, Iran, significant differences were detected among the tested genotypes, with Saravan and RGC-936 genotypes producing 1167.9 and 2101ton ha^{-1}, respectively, in terms of seed yield. Other studies also noted significant variation in seed yield between different genotypes. Singla et al.[4] observed genotypic variation for seeds plant^{-1} and seed pod^{-1}, while Gresta et al.[14], Kalyani[56], and Punia et al.[57] reported significant differences in seed yield. High levels of genetic adaptability and seed production potential were also observed in RGC-936. Therefore, it could be recommended as a promising cultivar for use in various breeding programs to improve local stocks.

Simple effect of biochar

The significant impact of biochar on various plant traits, including SPAD, EL, plant height and root length, plant and root weight, leaf area, and absorption of all measured nutrients in the leaves, was revealed by the results of the mean comparison of the main effects of biochar (Table 5). The highest amount of these traits and the highest element uptake in guar were found at the highest level of biochar (10 ton ha^{-1}), while the lowest was observed in the control treatment (no biochar application), indicating the positive impact of biochar on these morphology and physiology characteristics. Similarly, applying biochar to silty clay soils enhanced tomato growth. The increase in water-holding capacity due to biochar application is a key factor in improving various growth parameters and yield under drought conditions [58]. The increase in biochar in the soil also increased leaf area, which is a crucial factor for the reception of solar radiation, water, and energy exchange in the plant[59]. Consequently, this increases the level of photosynthesis[60]. Biochar can improve soil fertility and cation exchange capacity which results in better root development, increased nutrient retention, and growth of plants[61]. In addition, the use of biochar can be even more beneficial for plant growth in low-quality soils[62]. Once biochar is introduced into the soil, it can change the form of nitrogen in the short term, allowing for increased availability of nitrogen in the soil. This is achieved through mineralization of resistant organic matter in the soil and immobilization of organic nitrogen[63]. According to Korai et al.[64], the application of biochar to soil can increase the total soil carbon from 2.27 to 2.78%, total nitrogen from 0.24 to 0.25%, and available phosphorus from 15.7 to 15.8 mg kg^{-1}. Furthermore, the extractable amounts of calcium, potassium, magnesium, and sodium can increase from 60 to 670%. It's worth noting that the use of biochar had a greater impact on the morphological traits, while cultivar types had more influence on functional traits. However, none of the yield and yield components were statistically affected by biochar. Ghorbani et al.[31] also found that mycorrhiza and rhizobium biofertilizers did not significantly affect the yield traits of guar under drought stress conditions. Mannan et al.[28] also reported similar results regarding the use of biochar under water stress conditions in soybean. The schematic model of the potential impacts of biochar amendment on plant performance under drought stress is illustrated in Fig. 3[65–68].

Interaction effect of irrigation treatments, cultivars, and biochar

According to the ANOVA results, the combined effect of irrigation levels and cultivar was significant on several plant factors, including branches plant^{-1}, clusters plant^{-1}, pods plant^{-1}, seeds plant^{-1}, 1000-seed weight, SPAD, and concentration of potassium. Table 6 indicates that when plants with the Saravan cultivar were treated with the Ir3 treatment, they showed the highest 1000-seed weight (51.5 gr), clusters per plant (13.9), and potassium uptake (71.0 mg g^{-1}). The branch plant^{-1} of the samples treated by Ir1 and Saravan cultivar was 9.8. The results also suggested that the highest number of clusters plant^{-1} (14.4) and number of pods plant^{-1} (78.0) were found when plants of the RGC-936 cultivar were irrigated with treatments Ir2 and Ir3, respectively. Furthermore, the combined effect of irrigation treatment and biochar levels was significant on the weight of roots and plants, plant height, clusters plant^{-1}, chlorophyll a content, SPAD, and concentrations of K^+ and Na^+.

Drought stress reduces the growth of seedlings, the transpiration of crops, stomatal conductance, leaf water potential, and root activities. All of these factors affect both the vegetative and reproductive yield as well as the harvest index[41,69]. In our current study, we observed that increasing drought intensity had a negative impact on the growth and productivity of guar cultivars (RGC-936 and Saravan). We found that the morpho-physiological parameters and yield components of guar plants significantly decreased with increasing drought stress. Similar findings have been reported in many previous studies involving environmental stress exposure and cultivation practices in guar plants[41,70,71]. The decline in growth under longer drought duration was likely due to direct water limitation, which inhibited cell expansion and division[72–74]. There have been several studies that have looked into the benefits of adding biochar to soils, especially for plants under drought stress conditions. For instance, the addition of biochar has led to increased dry weight in *Quercus castaneifolia* by improving soil parameters and leaf photosynthesis[74]. Similarly, biochar has been found to improve the leaf photosynthetic rate and stomatal conductance in soybean[75]. Biochar is a soil amendment made through high-temperature pyrolysis of straw, which can enhance soil structure and increase soil carbon sequestration. This process can significantly improve nitrogen use efficiency, reduce warming potential, emission intensity in agricultural processes, and ultimately lead to increased crop yields[76].

The findings of experiment reveal that the Ir2B3 treatment resulted in the highest chlorophyll a content (1.7 mg g^{-1}), Na^+ value (60.6 mg g^{-1}), SPAD index (102.4), root weight (5.1 g), plant weight (118.8 g), plant height (67.8 cm), and number of clusters plant^{-1} (16.5). Moreover, the highest concentration of K^+ in leaves (81.4 mg g^{-1}) was observed in samples that were treated with 10 ton ha^{-1} of biochar and an irrigation cycle of 17 days, in the Ir3B3 treatment (Table 7). When comparing the average effects of guar cultivars and biochar (Fig. 2), it was observed that in B3 levels, cultivar types did not significantly affect root weight, which was highest in cv2B3 treatments (3.9 g). Similarly, the highest and lowest SPAD values were observed in cv1B3 (98.8) and cv2B1 (83.8) treatments, respectively. However, no significant differences were observed in various other characteristics of the tested samples due to other interaction treatments.

Multivariate statistical analysis

The findings of Pearson correlation analysis on various traits of different guar cultivars under different irrigation and biochar levels have been summarized in Table 8. The analysis suggests that plant weight ($r=0.288$), plant length ($r=0.413$), root weight ($r=0.357$), root length ($r=0.463$), stem diameter ($r=0.359$), seed pod^{-1} ($r=0.487$), branches plant^{-1} ($r=0.658$), and 1000-seed weight ($r=0.600$) have a moderate correlation with seed yield. On the other hand, pod plant^{-1} ($r=0.830$) and seed plant^{-1} ($r=0.840$) have a strong correlation with seed yield. However, pod length, branches plant^{-1}, and gum content have shown a positive but not significant relationship with seed yield. Moreover,

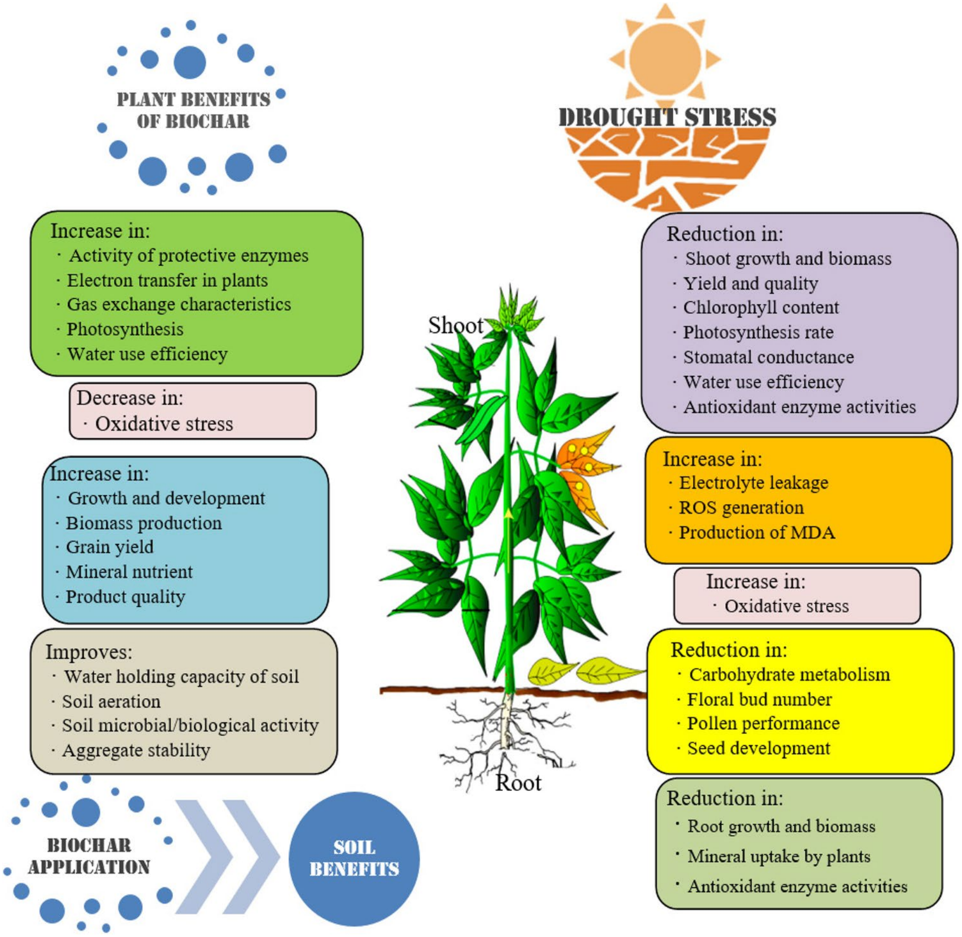

Figure 3. Schematic representation of possible impacts of biochar application on growth and metabolism of plants under drought stress. Drought stress disturbs the gas exchange characteristics, transpiration rate, stomata density, chlorophyll contents, soil microbial activities, soil aeration, and nutrients, thereby leadings to a significant reduction in plant productivity. Biochar application increases antioxidant activities, membrane stability, photosynthesis, water use efficiency, gas exchange characteristics, water holding capacity, genes expression, and osmolytes accumulation and leads to a significant increase in drought tolerance.

the analysis has also revealed that 1000-seed weight has a positive association with the number of branches ($r=0.356$), the number of clusters ($r=0.311$), and seed yield ($r=0.600$). This implies that increasing seed weight will inevitably lead to an increase in seed yield. The results mentioned above are consistent with previous studies on cluster beans. Girish et al. [77] found that the number of clusters and pods per plant, as well as the weight of 100 seeds, were all similar. Rakesh et al.[78] reported that the number of seeds pod^{-1} was correlated with EL, canopy temperature, SPAD, and leaf RWC. Meftahizadeh et al.[20] found that plant height, branches plant^{-1}, pods plant^{-1}, and seeds plant^{-1} were all similar to those found in guar. Chlorophyll b content is positively and moderately correlated with chlorophyll a ($r=0.630$), and EL is positively correlated with seeds in pods ($r=0.520$), canopy temperature ($r=0.613$), SPAD ($r=0.640$), and leaf RWC ($r=0.608$). The length of the pod is positively but weakly correlated with the number of seeds pod^{-1} ($r=0.290$), plant weight ($r=0.291$), root weight ($r=0.331$), and root length ($r=0.322$). Although gum content is not significantly correlated with seed yield, 1000-seed weight, and the number of seeds plant^{-1}, it is positively associated with morphological and physiological traits such as plant and root weight, plant length, stem diameter, canopy temperature, RWC, and EL. It should be noted, however, that increasing seed yield does not increase the percentage of gum, which contradicts the findings of Meftahizadeh et al.[43] and Gresta et al.[79].

According to Meftahizadeh and Asareh[40], the quality of crops can be influenced by the temperature during planting and ecological conditions of different cultivars. They found a strong correlation between various traits, such as the percentage of gum, seed yield, pod plant^{-1}, 1000-seed weight, and clusters plant^{-1}. These traits were used as independent variables in a stepwise multiple linear regression model with seed yield as the dependent variable (Table 9). The model revealed that all coefficients were statistically significant, except for pod plant^{-1} and cluster plant^{-1}. To obtain the correct coefficients, these two variables were removed from the model, and the regression model was repeated. The model provided by this regression fitting was found as Eq. 1, which explained 94.1% of the variation in seed yield. Therefore, selecting genotypes based on these two traits can help improve crop yield.

$$\text{Seed yield} = -1995.83 + 4.57 \times (\text{seed plant}^{-1}) + 44.42 \times (1000 - \text{seed weight}),\ R = 0.971 \tag{4}$$

Traits	PW	RW	RL	PL	CP	BP	PodL	SD	Spod	SW	SP	SY	PP	SPAD	Tem	RWC	EL	Cl a	Cl b
RW	0.817**																		
RL	0.632**	0.651**																	
PL	0.781**	0.652**	0.620**																
CP	0.442**	0.559**	0.479**	0.552**															
BP	0.344*	0.185	0.225	0.122	0.188														
PodL	0.291*	0.331*	0.322*	0.132	0.096	0.168													
SD	0.398**	0.519**	0.360**	0.503**	0.357**	0.195	0.236												
Spod	0.174	0.247	0.375**	0.167	0.204	-0.091	0.290*	0.047											
SW	0.191	0.246	0.251	0.263	0.311*	0.356**	0.109	0.149	-0.002										
SP	0.278*	0.511**	0.482**	0.394**	0.646**	-0.182	0.188	0.331*	0.657**	0.139									
SY	0.288*	0.537**	0.463**	0.413**	0.658**	0.050	0.0189	0.359**	0.487**	0.600**	0.840**								
PP	0.280*	0.533**	0.473**	0.432**	0.720**	-0.195	0.126	0.393**	0.435**	0.191	0.957**	0.830**							
SPAD	-0.172	-0.088	0.138	-0.090	-0.088	-0.517**	0.078	-0.182	0.394**	-0.141	0.306*	0.110	0.243						
Tem	-0.328*	-0.312*	-0.112	-0.478**	-0.312*	-0.189	0.086	-0.383**	0.325*	-0.198	-0.013	-0.127	-0.144	0.381**					
RWC	0.597**	0.471**	0.193	0.640**	0.320*	0.192	-0.014	0.487**	-0.192	0.158	-0.009	0.083	0.053	-0.460**	-0.656**				
EL	-0.026	-0.091	0.214	-0.079	-0.097	-0.046	0.160	-0.151	0.526**	-0.061	0.249	0.086	0.126	0.640**	0.613**	-0.608**			
Cl a	0.454**	0.298*	0.145	0.481**	0.263	0.212	-0.008	0.192	0.103	-0.064	0.135	0.081	0.113	-0.150	-0.183	0.389**	-0.057		
Cl b	0.168	0.122	0.017	0.252	0.238	-0.004	-0.096	0.044	-0.014	0.052	0.164	0.199	0.205	-0.059	-0.031	0.053	0.052	0.630**	
Gum	0.366**	0.364**	0.245	0.584**	0.188	-0.092	0.076	0.411**	-0.018	0.144	0.139	0.181	0.184	-0.119	-0.463**	0.581**	-0.383**	0.229	0.021

Table 8. Pearson correlation analysis results among studies traits in different guar cultivar under various irrigation and biochar levels. ** and * correlation is significant at the 0.01 and 0.05 levels, respectively; PW: plant weight, RW: root weight, RL: root length, PL: plant length, CP: clusterplant^{-1}, BP: branch plant^{-1}, PodL: pod length, SD: stem diameter, Spod: seed pod^{-1}, SW: 1000-seed weight, SP: seed plant^{-1}, SY: seed yield, PP: pod plant^{-1}, SPAD: chlorophyll index, Tem: canopy temperature, RWC: relative leaf water content, EL: electrolyte leakage, cl. A: chlorophyll a, cl. B: chlorophyll b, gum: gum content.

Model	Unstandardized Coefficients		Standardized Coefficients	*t*	Sig.
	B	Std. Error	Beta		
(Constant)	-1989.947	163.367	-	-12.181	0.000
Pod plant^{-1}	-2.391	5.707	-0.056	-0.419	0.677
Seed plant^{-1}	4.803	0.717	0.810	6.697	0.000
Cluster plant^{-1}	5.361	12.397	0.022	0.432	0.667
1000-seed weight	44.259	3.243	0.491	13.649	0.000

Table 9. Regression coefficients to identify traits affecting seed yield.

	Component				
	1	2	3	4	5
PW	0.148	0.419	0.738	0.332	0.008
PL	0.349	0.575	0.495	0.344	-0.073
CP	0.684	0.289	0.178	0.256	0.241
BP	-0.256	0.017	0.455	0.219	0.697
SW	0.292	0.096	0.177	-0.029	0.693
SP	0.952	-0.033	0.172	0.054	-0.124
SY	0.895	0.047	0.175	0.042	0.293
PP	0.954	0.105	0.079	0.063	-0.050
Gum	0.152	0.722	0.158	-0.050	-0.171
RWC	-0.051	0.875	0.238	0.183	0.000
EL	0.164	-0.757	0.341	0.095	-0.256
Cla	0.022	0.215	0.178	0.851	-0.091
Clb	0.189	-0.024	-0.153	0.858	0.018
SPAD	-0.012	-0.010	0.361	0.207	-0.701
Tem	-0.045	-0.790	0.066	-0.202	-0.171
Rw	0.443	0.408	0.613	0.138	0.045
Spod	0.542	-0.387	0.395	-0.006	-0.278
SD	0.300	0.519	0.354	-0.019	0.049
RL	0.422	0.116	0.696	0.042	0.063
PodL	0.079	-0.115	0.645	-0.214	0.049

Table 10. Rotated component matrix for the PCA loadings of studies traits. PW, plant weight; RW, root weight; RL, root length; PL, plant length; CP, cluster plant^{-1}; BP, branch plant^{-1}; PodL, pod length; SD, stem diameter; Spod, seed pod; SW, 1000-seed weight; SP, seed plant^{-1}; SY, seed yield; PP, pod plant^{-1}; SPAD, chlorophyll index; Tem, canopy temperature; RWC, relative leaf water content; EL, electrolyte leakage; Cl. a, chlorophyll a; Cl. b, chlorophyll b; Gum, gum content.

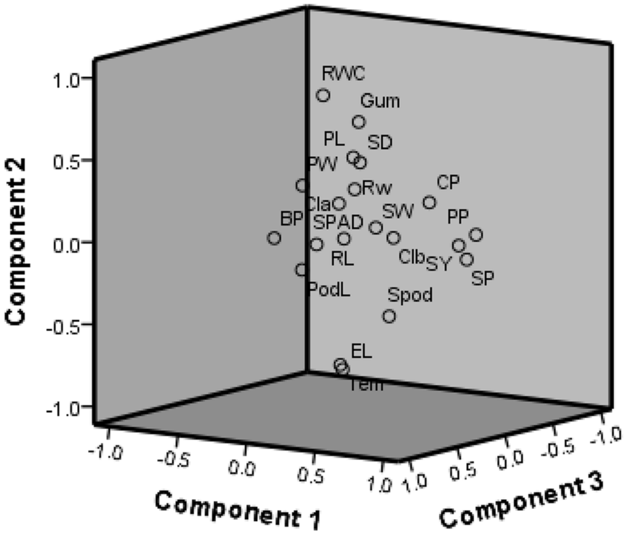

Figure 4. Factor distribution plot after varimax rotation for measured traits.

The study found that the number of seeds in the plant has a greater impact on seed yield compared to the 1000-seed weight. This is based on the fact that the number of seeds in the plant had a higher standardized regression coefficient (β = 0.810) than the 1000-seed weight (β = 0.491). This conclusion agrees with the results of Meftahizadeh and Asareh[40]. The regression and correlation results are also consistent with each other. The results of the principal component analysis (PCA) after varimax rotation of the data are presented in Table 10; Fig. 4. The analysis identified five main components with eigenvalues greater than 1, which explain 74.58% of the total variance. PC1 accounted for 21.17% of the system variance with strong positive loading for cluster plant^{-1}, seed plant^{-1}, seed pod^{-1}, pod plant^{-1}, and seed yield. PC2 explained 18.78% of the variance and showed strong loading for root length, gum content, RWC, EL, canopy temperature, and stem diameter. PC3 accounted for 15.36% of the variance with a strong loading for plant and root weight, root length, and pod length. PC4 explained 10.03% of the variance and showed strong loading for chlorophyll a and b. Finally, PC5 accounted for 1.84% of the variance with strong loading for branch plant^{-1}, 1000-seed weight, and SPAD.

Conclusions

Guar is a crop that can withstand extreme heat and drought, making it a valuable source of income for farmers in regions with limited water resources. It is also used as animal feed, and its leaves and pods are consumed as a vegetable in some cultures. Overall, it is an important crop with a wide range of uses and benefits, for both industrial and agricultural purposes. In a recent study conducted in an arid region of Iran, the effect of biochar as a soil amendment, and low irrigation treatment was investigated on two commercial and local cultivars of guar. The study found that a reasonable production of guar seed can be obtained under reduced irrigation conditions. On average, the Ir3 irrigation treatment produced the highest guar seed yield (1921.8 kg ha^{-1}). Compared to the Ir3 regime, the Ir1 and Ir2 treatments resulted in an 8.5% and 12.8% decrease in guar seed yield, respectively. However, as the irrigation cycle lengthened, water use efficiency showed an increasing trend. For instance, irrigating for 17 and 14 days increased water use efficiency by 60% and 40%, respectively, compared to the control treatment. Among the two cultivars, RGC-936 performed slightly better than Saravan in terms of growth and seed yield and yield components. Although, the 1000-seed weight, the plant weight, and the number of branches were higher in Saravan. The study results suggest that biochar was more effective than cultivars in improving morphological traits, while cultivars had an impact on yield and yield components. The addition of biochar could help improve physiological and morphological traits under reduced irrigation conditions, thus having a positive effect on water stress alleviation, guar growth, and leaf nutrient uptake. However, the three-way interaction between guar cultivars, irrigation treatments, and biochar was not significant for all the traits tested. In contrast, the two-way interaction between Ir2×B3 showed the maximum results in the studied region. Therefore, adding biochar could improve guar production under reduced irrigation conditions in the arid irrigated agriculture of central Iran. It would also help alleviate water stress and have a positive effect on the physiology and morphology characteristics of guar, but not on the seed yield characteristics.

Data availability

All the data generated/ analyzed during the study are available with the corresponding author on reasonable request.

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References

1. Avola, G., Riggi, E., Trostle, C., Sortino, O. & Gresta, F. Deficit irrigation on guar genotypes (Cyamopsis tetragonoloba (L.) Taub.): effects on seed yield and Iater use efficiency. *Agronomy***10**(6), 789 (2020).
2. Soltani-Gerdefaramarzi, S., Beik-Khormizi, V., Azizian, A. & Yarami, N. Effect of deficit irrigation with treated wastewater on water use efficiency, nutrient uptake, and growth of pistachio seedlings in an arid area. *J. Soil. Sci. Plant. Nutr.***21**(3), 2153–2163 (2021).
3. Ashraf, M. Y., Akhtar, K., Sarwar, G. & Ashraf, M. Role of the rooting system in salt tolerance potential of different guar accessions. *Agron. Sustain. Dev.***25**, 243–249 (2005).
4. Singla, S. et al. Growth and yield of guar (*Cyamopsis tetragonoloba* L.) genotypes under different planting dates in the semi-arid Southern High Plains. *Am. J. Plant. Sci.***7**(8), 1246–1258 (2016).
5. Soltani-Gerdefaramarzi, S., Alemzadeh, A., Yarami, N. & Dehestani-Ardakani, M. The Effects of Irrigation Methods and Water Quality on Soil Chemical properties and Leaf Nutrient Uptake of Lavandula (*Lavandula angustifolia* L.) in an Arid Region. *J. Plant Growth Regul.***42**(2), 1256–1265 (2023).
6. MacMillan, J., Shrestha, R., Adams, C. B., Hinson, P. O. & Trostle, C. The root system of guar: spatial and temporal analysis of root and nodule development. *Ann. Appl. Biol.***179**(3), 278–287 (2021).
7. Pathak, R. & Roy, M. M. Climatic responses, environmentalindices and interrelationships between qualitative and quantitative traits inclusterbean Cyamopsis tetragonoloba (L) Taub. under arid conditions. *Proc. Natl. Acad. Sci. India. Sect B. Biol. Sci.***85**(1), 147–154 (2015).
8. Khan, Z. et al. The application of biochar alleviated the adverse effects of drought on the growth, physiology, yield and quality of rapeseed through regulation of soil status and nutrients availability. *Ind. Crops Prod.***171**, 113878 (2021).
9. Shetty, R., Vidya, C. S. N., Prakash, N. B., Lux, A. & Vaculik, M. Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review I. *Sci Total Environ.***765**, 142744 (2021).
10. Besharati, J., Shirmardi, M., Meftahizadeh, H., Ardakani, M. D. & Ghorbanpour, M. Changes in growth and quality performance of Roselle (*Hibiscus sabdariffa* L.) in response to soil amendments with hydrogel and compost under drought stress. *South. Afr. J. Bot.***145**, 334–347 (2022).
11. Das, S. K., Ghosh, G. K. & Avasthe, R. *Valorizing biomass to engineered biochar and its impact on soil, plant, water, and microbial dynamics: a review* 1–17 (Biomass conversion and biorefinery, 2020).
12. Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R. & Lehmann, J. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environ. Sci. Technol.***44**(2), 827–833 (2010).
13. Christou, A. et al. *Effects of biochar derived from the pyrolysis of either biosolids, manure or spent coffee grounds on the growth, physiology and quality attributes of field-grown lettuce plants* Vol. 26, 102263 (Environmental Technology & Innovation, 2022).
14. Gresta, F. et al. Effects of sowing times on seed yield, protein and galactomannans content of four varieties of guar (*Cyamopsis tetragonoloba* L.) in a Mediterranean environment. *Ind. Crops Prod.***41**, 46–52 (2013).
15. Chiofalo, B. et al. Qualitative profile of degummed guar (*Cyamopsis tetragonoloba* L.) seeds grown in a Mediterranean area for use as animal feed. *J. Anim. Physiol. Anim. Nutr.***102**(1), 260–267 (2017).
16. Alshameri, A., Al-Qurainy, Fahad., Gaafar, A-R., Khan, Salim., Nadeem, Mohammad., Alansi, S. Identification of Heat-Responsive Genes in Guar [Cyamopsis tetragonoloba (L.) Taub]. *Int. J. Genomics*. **2020**, 3126592. https://doi.org/10.1155/2020/3126592 (2020).
17. Lubbe, A. & Verpoorte, R. Cultivation of Medicinal and aromatic plants for Specialty Industrial materials. *Ind. Crops Prod.***34**, 785–801 (2011).

18. Mudgil, D., Barak, S. & Khatkar, B. S. Guar Gum: Processing, Properties and Food Applications-A Review. *J. Food Sci. Technol.***51**, 409–418 (2011).
19. Hasan, M. L., Abidin, N. A. Z. & Singh, A. The rheological performance of guar gum and castor oil as additives in water-based drilling fluid. *Mater. Today. Proc.***5**(10), 21810–21817 (2018).
20. Meftahizadeh, H., Ghorbanpour, M. & Asareh, M. H. Changes in phenological attributes, yield and phytochemical compositions of guar (*Cyamopsis tetragonoloba* L.) landaraces under various irrigation regimes and planting dates. *Sci. Hortic.***256**, 108577 (2019).
21. Acharya, B. R., Sandhu, D., Dueñas, C., Ferreira, J. F. & Grover, K. K. Deciphering molecular mechanisms involved in salinity tolerance in guar (*Cyamopsis tetragonoloba* (L.) Taub.) using transcriptome analyses. *Plants***11**(3), 291 (2022).
22. Garcia, A., Grover, K., VanLeeuwen, D., Stringam, B. & Schutte, B. Growth and Performance of Guar (Cyamopsis tetragonoloba (L.) Taub.) Genotypes under Various Irrigation Regimes with and without Biogenic Silica Amendment in Arid Southwest US.. *Plants***12**(13), 2486 (2023).
23. Akhtar, S. S., Li, A. & Liu, F. Biochar enhances yield and quality of tomato under reduced irrigation. *Agric. Water Manage.***138**, 37–44 (2014).
24. Tanure, M. M. C. et al. *Soil Water retention, physiological characteristics, and growth of maize plants in response to biochar application to soil* Vol. 192, 164–173 (Soil and Tillage Research, 2019).
25. Hashem, A. et al. Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. *Saudi J. Biol. Sci.***26**(3), 614–624 (2019).
26. Zulfiqar, B. et al. Biochar enhances wheat crop productivity by mitigating the effects of drought: insights into physiological and antioxidant defense mechanisms. *PLoS One*. **17** (4), e0267819. https://doi.org/10.1371/journal.pone.0267819 (2022).
27. Jabborova, D. et al. Biochar and Arbuscular mycorrhizal fungi mediated enhanced drought tolerance in Okra (Abelmoschus esculentus) plant growth, root morphological traits and physiological properties. *Saudi J. Biol. Sci.***28**(10), 5490–5499 (2021).
28. Mannan, M. A., Mia, S., Halder, E. & Dijkstra, F. A. Biochar application rate does not improve plant water availability in soybean under drought stress. *Agric. Water Manag.***253**, 106940 (2021).
29. Saleem, K. et al. Biochar-Mediated Control of Metabolites and Other Physiological Responses in Water-Stressed Leptocohloa fusca. *Metabolites***13**(4), 511 (2023).
30. Zhu, J. et al. *Exploring the Potential of Biochar and Mulched Drip Irrigation with Plastic Film on Crop Yields in Water-Stressed Regions: a Global Meta-Analysis* 1–11 (Journal of Soil Science and Plant Nutrition, 2023).
31. Ghorbani, M., Ramazani, S. H. R., Fallahi, H. R. & Mousavi Koohi, S. M. Effect of Drought stress and bio-fertilizer on yield and yield components of Guar Cyamopsis tetragonoloba (L.) Taub. *J. Med. Plants By-product*. **8** (1), 13–19 (2019).
32. Nejad, N. H., Einali, A. & Ziaei, S. M. Reduction of drought stress effects on guar (*Cyamopsis tetragonoloba* L.) using ascorbic acid and calcium carbonate. *Legume Research-An Int. J.***46**(2), 171–175 (2023).
33. Mohanty, P. et al. Evaluation of the physiochemical development of biochars obtained from pyrolysis of wheat straw, timothy grass and pinewood: effects of heating rate. *J. Anal. Appl. Pyrol.***104**, 485–493 (2013).
34. Sabahelkheir, M. K., Abdelwahab, A. & Nouri Sulafa, H. Quality assessment of guar gum (endosperm) of guar (*Cyamopsis tetragonoloba*). *ISCA J. Biol. Sci.***1**(1), 67–70 (2012).
35. Arnon, D. I. Copper enzymes in isolated chloroplasts. Polyphenoloxidase in Beta vulgaris. *Plant Physiol.***24**(1), 1 (1949).
36. Blum, A. & Ebercon, A. Cell membrane stability as a measure of drought and heat tolerance in wheat 1. *Crop Sci.***21**(1), 43–47 (1981).
37. Jones, J. B. Jr, Wolf, B. & Mills, H. A. *Plant Analysis Handbook. A Practical Sampling, Preparation, Analysis, and Interpretation Guide* (Micro-Macro Publishing, Inc, 1991).
38. Olsen, S. R., Sommers, L. E. & Phosphorus, P. 403–430 In (eds Page, A. L. et al.) Methods of soil Analysis. Part 2. 2nd ed. Agronomy Monogr. 9. ASA and SSSA, Madison, WI. (1982).
39. Alexander, W. L., Bucks, D. A. & Backhaus, R. A. Irrigation water management for guar seed production. *Agron. J.***80**, 447–453 (1988).
40. Meftahizadeh, H. & Asareh, M. H. Comparison of native populations and commercial cultivars of guar (*Cyamopsis tetragonoloba* L.) for yield, yield components, and qualitative characteristics under different seasonal cultivation. *Iran. J. Med. Aromatic Plants*. **35** (3), 456–470 (2019). (In Persian).
41. Baiazidi-Aghdam, M. T., Mohammadi, H. & Ghorbanpour, M. Effects of nanoparticulateanatase titanium dioxide on physiological and biochemical performance of Linum usitatissimum (Linaceae) under well-watered and drought stress conditions. *Braz J. Bot.***39**, 139–146 (2016).
42. Meftahizadeh, H., Ghorbanpour, M. & Asareh, M. H. Comparison of morphological and phytochemical characteristics in guar (*Cyamopsis tetragonoloba* L.) landraces and cultivars under different sowing dates in an arid environment. *Ind. Crops Prod.***140**, 111606 (2019b).
43. Rocha, J. et al. Water yield and biomass production for on a eucalypt-dominated Mediterranean catchment under different climate scenarios. *J. For. Res.***34**, 1263–1278. https://doi.org/10.1007/s11676-022-01590-2 (2023).
44. Hernández, T., Chocano, C., Moreno, J. L. & García, C. *Use of Compost as an Alternative to Conventional Inorganic Fertilizers in Intensive Lettuce (Lactuca sativa L.) crops—Effects on soil and Plant*160pp.14–22 (Soil and tillage research, 2016).
45. Tabatabaei, S. H., Nafchi, R. F., Najafi, P., Karizan, M. M. & Nazem, Z. Comparison of traditional and modern deficit irrigation techniques in corn cultivation using treated municipal wastewater. *Int. J. Recycl Org. Waste Agric.***6**, 47–55 (2017).
46. Demir, A. D. & Sahin, U. *Effects of Different Irrigation Practices Using Treated Wastewater on Tomato Yields, Quality, Water Productivity, and soil and Fruit Mineral Contents*24pp.24856–24879 (Environmental Science and Pollution Research, 2017).
47. Schütz, M. & Fangmeier, A. Growth and yield responses of spring wheat (Triticum aestivum L. Cv. Minaret) to elevated CO_2 and water limitation. *Environ. Pollut.***114**(2), 187–194 (2001).
48. Khanzada, B. et al. Study of photosynthetic efficiency of some guar (*Cyamopsis tetragonoloba* L., Taub) genotypes grown under different water regimes. *Asian J. Plant. Sci.***2**(1), 127–131 (2003).
49. Hazzoumi, Z., Moustakime, Y. & Joutei, K. A. Effect of arbuscular mycorrhizal fungi (AMF) and water stress on growth, phenolic compounds, glandular hairs, and yield of essential oil in basil (*Ocimum gratissimum* L). *Chem. Biol. Technol. Agric.***2**(1), 1–11 (2015).
50. Draikewicz, M. Chlorophylase occurrence functions, mechanism of action, effect of extra and internal factors. *Phtosyth*. **30** (6), 321–337 (2004).
51. Kesahvarznia, R. et al. The impact of barley root structure and physiological traits on drought response. *Iran. J. Field Crop Sci.***45**(4), 553–563 (2014) (In Persian).
52. Gholinezhad, E. Effect of drought stress and stress modifier on biochemical traits of pot marigold (*Calendula officinalis* L). *Plant. Process. Function*. **8** (33), 213–228 (2019). (In Persian).
53. Bahador, M., Tadayon, M. R., Rafie-alhoseini, M. & Salehi, M. H. Changes of Canopy temperature and some physiological traits of hemp (*Cannabis sativa*) under Deficit Water stress and Zeolite Rates. *Environ. Stresses Crop Sci.***10**(2), 269–279 (2017) (In Persian).
54. Levitt, J. *Responses of Plants to Environmental Stresses. Volume II. Water, Radiation, salt, and Other Stresses (No. Ed. 2)* (Academic, 1980).
55. Fakhrabadi, H. & Khoshsimaie chinar, M. The Effect of Deficit Irrigation and Biochar on quantitative and qualitative characteristics of Basil. *Iran. J. Irrig. Drain.***15**(4), 941–954 (2021) (In Persian).
56. Kalyani, D. L. Performance of Cluster Bean genotypes under Varied Time of Sowing. *Legume Res.***35**, 154–158 (2012).

57. Punia, A., Yadav, R., Arora, P. & Chaudhury, A. Molecular and Morphological Characterization of Superior Cluster Bean (*Cyamopsis tetragonoloba*) varieties. *J. Crop Sci. Biotechnol.***12**, 143–148 (2009).
58. Kavitha, B. et al. Benefits and limitations of biochar amendment in agricultural soils: a review. *J. Environ. Manage.***227**, 146–154 (2018).
59. de Jesus, W. C., do Vale, F. X. R., Coelho, R. R. & Costa, L. C. Comparison of two methods for estimating leaf area index on common bean. *Agron. J.***93**(5), 989–991 (2001).
60. de la Riva, E. G., Olmo, M., Poorter, H., Ubera, J. L. & Villar, R. Leaf mass per area (LMA) and its relationship with leaf structure and anatomy in 34 Mediterranean Woody species along a water availability gradient. *PloS One*. **11** (2), e0148788 (2016).
61. Mishra, P. C. & Patel, R. K. Use of agricultural waste for the removal of nitrate-nitrogen from aqueous medium. *J. Environ. Manage.***90**(1), 519–522 (2009).
62. Van Zwieten, L. et al. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant. soil.***327**(1), 235–246 (2010).
63. Nelissen, V. et al. Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. *Soil Biol. Biochem.***55**, 20–27 (2012).
64. Korai, P. K. et al. Extractable pool of biochar controls on crop productivity rather than greenhouse gas emission from a rice paddy under rice-wheat rotation. *Sci. Rep.***8**(1), 802 (2018).
65. Wu, Y. et al. The critical role of biochar to mitigate the adverse impacts of drought and salinity stress in plants. *Front. Plant. Sci.***14**, 1163451. https://doi.org/10.3389/fpls.2023.1163451 (2023).
66. Park, J. H. et al. Biochar improves soil properties and corn productivity under drought conditions in South Korea. *Biochar*. **5**, 66. https://doi.org/10.1007/s42773-023-00267-1 (2023).
67. Wang, X., Zheng, W-L., Ma, X., Yu, F-H. & Li, M-H. Biochar aggravates the negative effect of drought duration on the growth and physiological dynamics of Pinus massoniana. *Front. Ecol. Evol.***11**, 1166538. https://doi.org/10.3389/fevo.2023.1166538 (2023).
68. Hazman, M. et al. Enhancing rice resilience to drought by applying biochar–compost mixture in low-fertile sandy soil. *Beni-Suef Univ. J. Basic. Appl. Sci.***12**, 74. https://doi.org/10.1186/s43088-023-00411-7 (2023).
69. Tashakorizadeh, M. et al. Physiological and biochemical mechanisms of grain yield loss in fumitory (*Fumaria parviflora* Lam.) Exposed to copper and drought stress. *Sci. Rep.***13**, 17934. https://doi.org/10.1038/s41598-023-45103-5 (2023).
70. Sanaei, S. et al. Cadmium and lead differentially affect growth, physiology, and metal accumulation in guar (*Cyamopsis tetragonoloba* L.) genotypes. *Environ. Sci. Pollut Res.*https://doi.org/10.1007/s11356-021-15968-y (2021).
71. Rahmati Ahmadabad, Z., Meftahizadeh, H., Shirmardi, M., Ghorbanpour, M. & Dehestani Ardakani, M. Intercropping improves yield and phytochemical attributes in guar (*Cyamopsis tetragonoloba* L.) and roselle (*Hibiscus Sabdarifa* L.) plants under nitrogen application. *South. Afr. J. Bot.***147**, 608–617 (2022).
72. Eilmann, B., Zweifel, R., Buchmann, N., Pannatier, G., Rigling, A. & E., and Drought alters timing, quantity, and quality of wood formation in scots pine. *J. Exp. Bot.***62**, 2763–2771. https://doi.org/10.1093/jxb/erq443 (2011).
73. Martinez-Sancho, E., Treydte, K., Lehmann, M. M., Rigling, A. & Fonti, P. Drought impacts on tree carbon sequestration and water use-evidence from intraannual tree-ring characteristics. *New. Phytol.* **236**, 58–70. https://doi.org/10.1111/nph.18224 (2022).
74. Zoghi, Z., Hosseini, S. M., Kouchaksaraei, M. T., Kooch, Y. & Guidi, L. The effect of biochar amendment on the growth, morphology and physiology of Quercus castaneifolia seedlings under water-deficit stress. *Eur. J. For. Res.***138**, 967–979. https://doi.org/10.1007/s10342-019-01217-y (2019).
75. Zhang, Y., Ding, J., Wang, H., Su, L. & Zhao, C. Biochar addition alleviate the negative effects of drought and salinity stress on soybean productivity and water use efficiency. *BMC Plant. Biol.***20**, 288. https://doi.org/10.1186/s12870-020-02493-2 (2020).
76. Agegnehu, G., Nelson, P. N. & Bird, M. I. The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. *Sci. Total Environ.***569–570**, 869–879. https://doi.org/10.1016/j.scitotenv.2016.05.033 (2016).
77. Girish, M. H. et al. Genetic variability studies in cluster bean [*Cyamopsis tetragonoloba* (L.) Taub]. *Karnataka J. Agricultural Sci.***26**(3), 442–443 (2013).
78. Rakesh, P., Manjit, S. & Henry, A. Stability, correlation and path analysis for seed yield and yield attributing traits in guar. *Indian J. Agric. Sci.***81**, 309–313 (2011).
79. Gresta, F., Avola, G., Cannavò, S. & Santonoceto, C. Morphological, biological, productive and qualitative characterization of 68 guar (Cyamopsis tetragonoloba (L.) Taub.) Genotypes. *Ind. Crops Prod.***114**, 98–107 (2018).

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Author contributions

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Statement on experimental research and field studies on plants

The cultivated plants sampled comply with relevant institutional, national, and international guidelines and domestic legislation of Iran.

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The authors declare no competing interests.

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