Article

Acidified Biochar as a Soil Amendment to Drought Stressed (*Vicia faba* L.) Plants: Influences on Growth and Productivity, Nutrient Status, and Water Use Efficiency

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Abstract: Drought is one of the major threats to global food security. Biochar use in agriculture has received much attention and improving it through chemical modification offers a potential approach for enhancing crop productivity. There is still limited knowledge on how acidified biochar influences soil properties, and consequently its influences on the agricultural productivity of drought stressed plants. The water use efficiency (I-WUE) of drought stressed faba beans was investigated through the effects of acidified biochar (ACBio) (a 3:100 (w:w) combination of citric acid and biochar) on soil properties, growth, productivity, nutrient uptake, water productivity (WP), and irrigation. Two field experiments (2016/2017 and 2017/2018) were conducted in saline soil (EC_e, 7.2 dS m^{−1}) on faba bean plants grown under three irrigation regimes (i.e., 100, 80, and 60% of crop evapotranspiration (ET_c)) combined with three levels of ACBio (0, 5, and 10 t ha^{−1}). Plants exposed to water stress presented a significant decrease in plant height, dry matter, leaf area, chlorophyll content (SPAD), the quantum efficiency of photosystem II (F_v/F_m , F_v/F_0 , and PI), water status (membrane stability index and relative water content), and seed yield. Acidified biochar soil incorporation improved soil properties (chemical and physical), plant growth, physiological responses, WP, I-WUE, and contents of N, P, K, and Ca. Results revealed that the application of ACBio at 10 t ha^{−1} and 5 t ha^{−1} significantly increased seed yield by 38.7 and 25.8%, respectively, compared to the control. Therefore, ACBio incorporation may find application in the future as a potential soil amendment for improving growth and productivity of faba bean plants under deficit irrigation.

Keywords: drought stress; soil properties; physiological responses; faba bean and irrigation water use efficiency

1. Introduction

In arid and semi-arid countries, water shortage has an extreme effect on agricultural production. Therefore, there is increasing attention to improve water efficiency in agriculture. In the Mediterranean area where irrigation water is essential for the production of crops, farmers are searching for new tools to save water by enhancing the efficiency of water use. Globally, the faba bean (*Vicia faba* L.) is characterized as one of the most important legumes crops due to its importance for soil fertility, human nutrition as a good source of vegetarian protein, animal feeding, and industry purposes, also playing a vital

role in the food chain. Moreover, it has become the most strategic crop due to its high income for farmers [1]. The seed of a faba bean is rich in carbohydrates (51–68%) [2] and proteins (28–30%) of dry matter [3]. In Egypt, the increasing quantity and quality of faba beans are major goals for meeting the demands of an increasing Egyptian population as faba beans are a main part of the diet of Egyptian people [4]. Water shortage has become a critical problem worldwide, especially in arid and semi-arid areas where water is required for growing crops [5]. In Mediterranean African countries, such as Egypt, the agriculture sector consumes nearly 80% of total water withdrawal. Therefore, developing policies is required to improve the efficiency of irrigation water use, while keeping the quantity and quality of crop production [6]. In the last decade, the challenge is the method of producing more yields from a restricted water supply. One way for attempting this problem is the approval of new practices that assist to improve water management, particularly under field conditions. Egypt faces various challenges, such as water scarcity initiated by human activities and environment variation, drought, and desertification. Therefore, emerging technical performs and using advanced irrigation-saving knowledge must be utilized for improving faba bean productivity. Deficit irrigation (DI) was initiated in agriculture to improve the efficiency of irrigated water [7–11]. Numerous researchers have documented the DI technique applied usually in water shortage conditions [10]. Much attention has been recently paid to sustainable agriculture development. Soil organic amendments are the most significant conservation agricultural practices for mitigating various abiotic stresses, for instance, drought, salinity, and heavy metals [11–18]. Biochar substances as a potential soil amendment in agriculture has been intensively reported in recent years to enhance plant growth and productivity as well as to alleviate the harmful impacts of different abiotic stresses and to improve soil structure and fertility [14,16,19–24]. A combination of acidified biochar and DI could be a promising practice among water management strategies for improving the efficiency of irrigation use. Biochar as organic amendments has a great role in improving soil aggregation, supplying nutrients, and motivating the microbial diversity and activity of soil [23,24]. The addition of biochar to soil has been revealed, in several experiments, to encourage soil alkalization by increasing pH values in acidic soil, which correspond to the increased contents of alkaline metals (i.e., Mg^{2+} , Ca^{2+} , and K^{+}) oxides in biochars [25–30]. Egyptian soil is usually categorized by slightly alkaline to alkaline, mostly due to high temperatures, little rainfall, low relative humidity, and a high evaporation rate, leading to corrupted soil [31]. Soil alkalinity is considered the greatest problem in semi-arid and arid zones like Egypt and characterized by high pH values (7.5–8.7) [32]. Alkaline soils are described by the reduced availability of macro and micronutrients (i.e., N, P, K, Cu, Fe, Zn, and Mn) and alkali stress generally includes a grouping of stresses, osmotic ion-induced damage, and increased soil pH [33–37]. Additionally, it has been widely reported that the supplying of biochar to soils has caused an increase of soil pH [38–40]. For these reasons, we added citric acid to citrus wood biochar (3:100 (w/w)) to decrease the pH of biochar from 8.82 to 7.12. To the best of our knowledge, this is the first attempt at investigating the combined effect of acidified biochar and deficit irrigation on faba beans. Thus, one of the main purposes of current investigation was to study how acidified biochar influences soil properties and consequently the growth and productivity, nutrient uptake, photosynthetic efficiency, and water use efficiency of drought-stressed faba bean plants.

2. Materials and Methods

2.1. Experimental Set-Up

In the successive growing seasons of 2016/17 and 2017/18, two field experiments were conducted at a private farm located in the El Fayoum region (latitudes 29°02' and 29°35' N and longitudes 30°23' and 31°05' E), Egypt. According to [37], the soil is classified as arid climatic conditions. Table 1 shows soil properties (physical and chemical) of the experimental location which were analyzed according to the methods of [38,39].

Table 1. Some initial physical properties of the studied soils.

Layer (cm)	Particle Size Distribution				Bd gcm^{-3}	K_{sat} cmh^{-1}	Soil Moisture Content at			ECe dS m^{-1}	pH	OM %	CaCO ₃ , %	N (%)	P (mg kg ⁻¹ Soil)	K (mg kg ⁻¹ Soil)
	Sand %	Silt %	Clay %	Texture Class			FC %	W.P %	A. W %							
0–25	76.50 ± 0.72	12.50 ± 0.47	11.00 ± 0.49	LS	1.56 ± 0.06	2.13 ± 0.08	23.33 ± 1.2	10.73 ± 0.39	12.60 ± 0.54	7.23 ± 0.12	7.65 ± 0.11	1.53 ± 0.04	4.53 ± 0.23	0.003 ± 0.00	535.30 ± 23	48.36 ± 2.06
25–50	75.00 ± 0.69	12.80 ± 0.51	12.20 ± 0.61	LS	1.62 ± 0.04	1.98 ± 0.09	21.12 ± 1.1	9.50 ± 0.36	11.62 ± 0.46	6.98 ± 0.13	7.74 ± 0.09	1.20 ± 0.03	4.21 ± 0.22	0.003 ± 0.00	544.61 ± 19	45.31 ± 1.99

LS = loamy sand, Bd = bulk density, Ksat = hydraulic conductivity FC = field capacity, W.P = wilting point, A.W = available water, ECe = the average of electrical conductivity, and O.M = organic matter.

The experiments were conducted in randomized block design with split plot. Treatments were divided into three irrigation water applications (IWA) and three acidified biochar (ACBio) rates. Irrigation was applied as a percentage of the ETc, representing one of the following three treatments: ($I_{100} = 100\%$, $I_{80} = 80\%$, and $I_{60} = 60\%$ of ETc). Irrigation treatments were distributed in the main plots, while acidified biochar treatments namely (ACBio₀ = 0 t ha⁻¹, as a control, ACBio₅ = 5 t ha⁻¹, and ACBio₁₀ = 10 t ha⁻¹) were allotted in the sub-plots.

Three weeks before sowing faba beans, ACBio (3:100 (w/w/) combination of citric acid, and citrus wood biochar] was incorporated in the soil. Properties of the acidified biochar (ACBio) used in these experiments were presented in Table 2. A total of 9 treatments were replicated three times and the total experimental plots were 27. The experimental plot area was 18 m (length) × 0.8 m (row width) (14.4 m²), each plot involved 3 planting rows and the space between plants within rows was 15 cm.

Table 2. Acidified biochar properties.

Attribute	Unit	Value
BD	g cm ⁻³	0.79
EC	dS m ⁻¹	1.62
pH		7.12
MC		19.60
C	%	42.70
Ash		35.70
CEC	cmol+/kg	46.50
Macronutrients		
N	%	1.48
P		0.078
K		3495
Ca		4435
Na		<11
Micronutrients		
Zn	mg kg ⁻¹	74.00
Fe		83.00
Mn		569.00
Cu		21.00

BD is the bulk density, MC is moisture content, and CEC is the cation exchange capacity.

2.2. Agronomic Management

Healthy seeds of faba bean (*Vicia faba*. L., cultivar Sakha 1) were sown on 8 and 10 October of 2016/17 and 2017/18 and harvested on 15 and 20 April of 2016/2017 and 2017/2018. The used system of irrigation was drip irrigation and 2 drip-lines placed 0.5 m apart in each elementary test plot. Irrigation treatments were started after full germination. Calcium superphosphate (15.5% P₂O₅), as a source of phosphorus (370 kg ha⁻¹) was added to the soil through the preparation of seedbed 150 kg ha⁻¹ in the form of ammonium nitrate (33.5% N), added in 2 doses through the growing seasons (20 and 40 days after sowing) as a source of nitrogen. In addition, 125 kg ha⁻¹ potassium sulphate (50% K₂O) was added after 75 days of the sowing date. All cultural practices were done according to recommendations of the Ministry of Agriculture, Egypt.

2.3. Irrigation Water Applied (IWA)

The amounts of water were determined according to [40] by using the following equation:

$$IWA = \frac{A \times ETc \times Ii}{Ea \times (1 - LR)} \quad (1)$$

where IWA is the irrigation water applied (m³), A is the plot area (m²), ETc is the evapo-transpiration (mm d⁻¹), Ii is the irrigation interval (day), Ea is the application efficiency

(%), and LR is the leaching requirements. ETc was estimated using the crop coefficient according to [40] equation:

$$ETc = K_{pan} \times E_{pan} \times K_c \quad (2)$$

where K_{pan} = pan evaporation coefficient, E_{pan} = evaporation from the Class A pan (mm d^{-1}), and K_c = crop coefficient.

2.4. Growth, Physiological, and Water Statutes Measurements

A total of 90 days after sowing, date samples of faba bean plants were collected from plots to determine the number of leaf per plant¹, plant height, number of branches per plant, leaf area, and dry weight per plant¹. Chlorophyll fluorescence (F_v/F_m , F_v/F_0 , and PI), as a convenient tool to assess photosynthetic efficiency, was determined according to [41,42] by Handy PEA, Hansatech Instruments (Ltd., Kings Lynn, UK). The values of membrane stability index (MSI%) and relative water content (RWC%) were determined according to [43,44] respectively. SPAD chlorophyll meter (SPAD-502; Minolta, Osaka, Japan) was used to determine the relative contents of chlorophyll.

2.5. Nutrients Determinations

The leaf nutrient contents (N, P, K, Ca, and Na) of faba beans were measured after being oven dried and wet digestion with HNO_3 and H_2O_2 samples were analyzed for P content spectrophotometrically [45] and for K^+ , Ca^{2+} , and Na^+ contents by Flame photometry (Gallenkamp Co., London, UK). The N content was estimated by Kjeldahl digestion method (Ningbo Medical Instruments Co., Ningbo, China).

2.6. Yield, Water Productivity, and Irrigation-Water Use Efficiency

At the harvesting stage, 10 randomly guarded plants were taken from each plot and used to determine yield components, i.e., number of pods per plant, pods weight plant⁻¹, and 100-seed weight. Seeds of all plants per plot were utilized to determine seed yield (t ha^{-1}). Water productivity (WP) and irrigation water use efficiency (I-WUE) indices were calculated using the following equations:

$$WP = \frac{\text{seed yield (Kg ha}^{-1}\text{)}}{\text{water applied (mm)}}, \quad (3)$$

$$I - WUE = \frac{\text{seed yield (Kg ha}^{-1}\text{)}}{\text{evapotranspiration (mm)}}. \quad (4)$$

2.7. Statistical Analysis

The results were statistically analyzed according to [46] using ANOVA procedures in a GenStat statistical package (version 11) (VSN International Ltd., Oxford, UK).

3. Results and Discussion

3.1. Effect of Acidified Biochar on Soil Characteristics

Data presented in Table 3 show the impact of ACBio application on soil physico-chemical properties. Soil bulk density, ECE, and pH strongly declined with increasing ACBio applications. Furthermore, the total porosity, field capacity (FC %), nitrogen content (N %), phosphorus (P), and potassium (K) (mg kg^{-1} soil) increased by adding ACBio (Table 3). Data revealed that ECE values decreased from 7.2 at control to 6.96 and 6.73 at ACBio₅ and 10 t ha^{-1} , as an average for S_I and S_{II} years, respectively. Likewise, soil pH decreased from 7.69 at ACBio₀ to 7.50 and 7.35 at the rate of ACBio₅ and 10 t ha^{-1} , respectively. The values of bulk density decreased (from 1.55 to 1.47 and 1.44 g cm^{-3}) when ACBio applications increased from 0 to 5 and 10 t ha^{-1} . In contrast, organic matter (OM %) was increased gradually from 1.19% to 1.79 and/or 2.0% with the increasing ACBio application from 0 to 5 and 10 t ha^{-1} , respectively.

Table 3. Effect of acidified biochar rates on some physical and chemical properties at harvesting stage for S_I (2016/17) and S_{II} (2017/18) seasons.

ACBio (t h ⁻¹)	ECe (dS m ⁻¹)	Soil pH	O.M %	N (%)	P (mg kg ⁻¹ Soil)	K (mg kg ⁻¹ Soil)	Total Porosity %	Bulk Density g cm ⁻³	FC %
S _I (2016/17)									
ACBio ₀	7.30 ± 0.88 a [†]	7.70 ± 1.12 a	1.18 ± 0.11 c	0.003 ± 0.00 c	518.54 ± 23.1 b	41.00 ± 3.51 c	32.21 ± 2.88 b	1.54 ± 0.12 a	22.24 ± 2.14 b
ACBio ₅	7.02 ± 1.13 b	7.52 ± 0.98 b	1.86 ± 0.15 b	0.007 ± 0.00 b	698.68 ± 25.31 a	49.42 ± 3.62 b	37.71 ± 3.14 a	1.49 ± 0.11 b	26.17 ± 3.10 ab
ACBio ₁₀	6.79 ± 0.97 c	7.38 ± 1.21 c	2.01 ± 0.12 a	0.021 ± 0.00 a	647.21 ± 32.1 a	55.68 ± 4.2 a	38.00 ± 3.41 a	1.45 ± 0.11 b	27.45 ± 2.84 a
S _{II} (2017/18)									
ACBio ₀	7.10 ± 1.11 a	7.67 ± 1.03 a	1.20 ± 0.10 c	0.003 ± 0.00 c	526.24 ± 28.63 b	42.34 ± 4.12 c	33.66 ± 2.13 b	1.56 ± 0.11 a	24.32 ± 2.45 b
ACBio ₅	6.90 ± 1.01 b	7.48 ± 1.11 b	1.71 ± 0.12 b	0.008 ± 0.00 b	610.14 ± 27.89 a	53.67 ± 4.65 b	38.21 ± 2.56 a	1.44 ± 0.13 b	27.67 ± 1.63 ab
ACBio ₁₀	6.66 ± 1.20 c	7.31 ± 1.17 c	1.98 ± 0.01 a	0.022 ± 0.00 a	659.43 ± 33.24 a	58.37 ± 3.89 a	39.26 ± 3.11 a	1.43 ± 0.12 b	29.67 ± 2.04 a

[†] Treatment means with the same letter are not significant at the $p \leq 0.05$ level.

O.M means organic matter and F.C means field capacity. The N, P, and K contents increased in ACBio₅ or ACBio₁₀ compared with the control. Among the integrative treatments, the application of 10 t ha⁻¹ was the best treatment and soil contents of N, P, and K were 133, 653.3, and 57.02% (mg kg⁻¹ soil), respectively. On the other hand, the addition of ACBio at 5 and 10 t ha⁻¹ increased the total porosity by 15.3 and 17.3% and field capacity by 15.6 and 22.7%, compared with the control as an average for both seasons. The improvements of soil quality after amendment with acidified biochar could be clarified by an increase in the nutrient adding and retention as a result of their supply to the soil [47–49]. These findings are in harmony with [50]. They concluded that some physical and chemical soil properties (total porosity, water holding capacity, bulk density, OM%, content of soil elements, and NPK) can likewise improve with the supplying of biochar.

3.2. Effect of Acidified Biochar on Nutrients Status of Faba Bean Plants

The addition of ACBio strongly increased faba bean leaf contents of macronutrients (N, P, K⁺, and Ca²⁺) compared to the non-treated soil. On the other hand, faba bean leaf Na⁺ content and Na⁺/K⁺ ratio decreased significantly by the addition of ACBio (Table 4) for both seasons. The Na⁺/K⁺ ratio and Na⁺ content in the leaves of faba bean decreased at ACBio₁₀ compared to ACBio₀. Data in Table 4 show that, with increasing ACBio application from 0 to 5 and 10 t ha⁻¹, the content of N increased by 20.9 and 22.5%, P by 25.4 and 16.9%, K by 20.7 and 28.0%, and Ca by 48.2 and 76% as an average for both seasons. These findings agree with those of [25]. They observed that the addition of biochar resulted in an increase of macronutrient uptake in maize. Furthermore, soil amended with 5 and 10 t ha⁻¹ of ACBio decreased Na and Na⁺/K⁺ by 27.0 and 27.6% for Na and by 40 and 43.3% for Na⁺/K⁺ compared with unamended soil, respectively. The results agree with [16,24]. They noted that biochar utilization has positive effects in decreasing Na⁺ uptake in plants. The increase of N, P, K, and Ca uptake by faba bean plants are most likely because of the induced improvement in chemical soil properties i.e., total N and available P₂O₅ contents, pH value, and CEC. Lower pH values of amended soil (Table 3) probably improved the nutrients status of faba bean plants. Hence this reduction in soil pH, lead to the increasing mineralization of organic materials and solubilization of elements particularly in the rhizosphere, which could have resulted in increased bioavailability of crucial elements in soil and ultimately their uptake and assimilation in faba bean plants. These results are in assenting with those obtained by [51]. The content of Na (g kg⁻¹) decreased gradually with increasing rates of acidified biochar (ACBio) from 19.1 in control to 13.8 in ABCio₁₀ in the second season. However, the ratio of Na⁺/K⁺ decreased under

ACBio₅ or ACBio₁₀ compared with the control. Biochar addition may or may not bring positive impacts on crop productivity depending on soil properties. Biochar integrated with fertilizers caused an increase in yields [52].

Table 4. Effect of acidified biochar rates on nutrients status (N, P, K Ca, Na, and Na⁺/K⁺ ratio) of faba bean plants for S_I (2016/17) and S_{II} (2017/18) seasons.

ACBio (t h ⁻¹)	N (g/kg)	P (g/kg)	K (g/kg)	Ca (g/kg)	Na ⁺ (g/kg)	Na ⁺ /K ⁺
S _I (2016/17)						
ACBio ₀	21.7 ± 0.43 b [†]	2.01 ± 0.36 c	21.5 ± 0.59 b	4.25 ± 0.25 b	19.5 ± 0.41 a	0.91 ± 0.12 a
ACBio ₅	26.2 ± 2.20 a	2.7 ± 0.22 a	25.3 ± 0.16 a	6.54 ± 0.61 a	14.2 ± 0.17 b	0.56 ± 0.11 c
ACBio ₁₀	26.7 ± 0.22 a	2.41 ± 0.16 b	26.7 ± 0.46 a	7.91 ± 0.75 a	14.7 ± 0.45 b	0.55 ± 0.10 b
S _{II} (2017/18)						
ACBio ₀	22.3 ± 0.36 b	2.13 ± 0.37 c	21.0 ± 0.69 b	5.25 ± 0.42 c	18.6 ± 0.28 a	0.89 ± 0.14 a
ACBio ₅	27.0 ± 1.50 a	2.73 ± 0.22 a	26.0 ± 0.17 a	7.54 ± 0.46 b	13.6 ± 0.23 b	0.52 ± 0.09 c
ACBio ₁₀	27.2 ± 0.10 a	2.55 ± 0.16 b	27.7 ± 0.42 a	8.81 ± 0.87 a	12.9 ± 0.32 b	0.47 ± 0.12 b

[†] Treatment means with the same letter are not significant at the $p \leq 0.05$ level.

3.3. Chlorophyll Relative Index (SPAD Value) and Chlorophyll Fluorescence

The interactive effects of ACBio and IWA on chlorophyll content (SPAD value), chlorophyll fluorescence (Fv/Fm), and the performance index (PI) were introduced in Figures 1 and 2. These parameters were affected negatively ($p \leq 0.05$), gradually with the increase of irrigation stress during both growing seasons ((S_I (2016/17) and S_{II} (2017/18)). On the other hand, the supplying of ACBio mitigated the harmful stress on the SPAD value, Fv/Fm, and PI created by a water deficit.

In both seasons, the highest values of SPAD, Fv/Fm, and PI were recorded when faba bean plants were well irrigated (I₁₀₀) and supplied with 10 t ha⁻¹ of ACBio. Likewise, lower values of SPAD, Fv/Fm, and PI were noted in ACBio + I_{60%} treatment. Faba bean plants had higher values of SPAD, Fv/Fm, and PI, produced higher pods number, pods weight (g), and consequently an increase in seed yield (t ha⁻¹). Many works stated that the values of chlorophyll fluorescence could be considered as a reliable tool for evaluating the fluctuations that occurred in the function of PSII in different stresses [53–55]. We observed a reduction in values of the efficiency of the photosystem's (Fv/Fm, and PI) relative content of chlorophyll (SPAD) under severe water conditions, which might have been due to the decrease in faba bean water status ((MSI% and RWC) (Figure 2)) necessary for photosynthesis. This is consistent with the results of other authors [54,56]. Various investigations have summarized that the disturbance of water supply led to a decrease in water content in absorption tissue, and thus, prompts photosynthetic discouragement [49,57,58].

Figure 1. Leaf chlorophyll fluorescence parameter of faba bean plants grown under irrigation treatments (I_{100} , irrigation with 100%; I_{80} , irrigation with 80%; and I_{60} , irrigation with 60% of ETC) and acidified biochar rates in 2016/17 and 2017/18 seasons. **(A)** Maximum quantum efficiency of PSII (F_v/F_m); **(B)** potential photochemical efficiency (F_v/F_0); and **(C)** performance index (PI). Vertical bars represent means of 3 replications $\pm$ S.E ($p \leq 0.05$). Columns marked by different letters are significantly different.

Figure 2. Effect of acidified biochar on (A) membrane stability index (MSI %), (B) relative water content (RWC %), and (C) chlorophyll content (SPAD) of faba bean plants grown under different irrigation treatments (I_{100%}, I_{80%}, and I_{60%} of ET_c) in S_I (2016/17) and S_{II} (2017/18) seasons. Vertical bars represent means of 3 replications $\pm$ S.E ($p \leq 0.05$). Columns marked by different letters are significantly different.

3.4. Faba Bean Water Status

The impacts of the ACBio and IWA on faba bean RWC% and MSI% indices are shown in Figure 2. Both indices were affected by both the ACBio and IWA ($p \leq 0.05$) and the highest values recorded during S_I (2016/17) than S_{II} (2017/18). According to the statistical analysis, the interaction between ACBio and IWA were positively affected ($p \leq 0.05$) on RWC% and MSI%. The values of RWC% and MSI% tended to decrease with increasing water stress. However, the addition of ACBio was found to modify the IWA-affected RWC% and MSI%. The highest values of RWC% and MSI% were obtained under $ACBio_{10} + I_{100}$ treatment for both seasons. Water stress had a strong impact on the RWC% and MSI% of faba bean leaves. RWC is a significant indicator of water status in crops or plants; it reveals the equilibrium between the transpiration rate and water supply to the leaf tissue [56,59,60]. Our results show that the addition of acidified biochar to saline soil under drought stress alleviated abiotic stresses by maintaining a higher RWC% and MSI% (Figure 2), lower Na^+/K^+ ratio (Table 4), and further improved the photosynthesis of faba bean leaves (Figure 1). This is consistent with the results of other authors [14,16,25] who reported increased plant water status because of the high adsorption capacity of biochar for water, which then increased the soil water content.

3.5. Faba Bean Growth Attributes

Plant height, leaves number $plant^{-1}$, number of branches $plant^{-1}$, dry matter $plant^{-1}$, and leaves area $plant^{-1}$ are analyzed statistically and presented in Tables 5 and 6. All growth parameters were highly significantly affected by IWA and ACBio. Among growth characteristics, leaves area and dry matter $plant^{-1}$ were affected by seasons. All growth traits were significantly affected by the interaction between the acidified biochar and irrigation regime. The highest values of all parameters had been registered when plants of faba bean were subjected to $I_{100\%}$ combined with $10 t ha^{-1}$ of acidified biochar ($ACBio_{10}$) as the average for both seasons. On the other hand, the lowest values were recorded under $I_{60\%} + ACBio_0$. Plant height, leaf number, branch number, leaf area, and dry matter were strongly reduced in $I_{60\%}$. Suppling ACBio clearly affected plant growth and the production of biomass. The enhanced growth traits may be due to the increase decomposition of the ACBio and mineralization of nutrients [61]. Our results showed that the utilization of 5 and $10 t ha^{-1}$ of ACBio significantly increased the growth attributes compared to $ACBio_0$. The enhancement observed in growth characteristics could be attributed to the nutrient availability after the application of ACBio.

Table 5. Means and standard errors for plant height, leaf number, branch number, dry matter, and leaf area.

Mean $\pm$ SE					
Item	Plant Height (cm)	Leave No.	Branch No.	Dry Matter (g)	Leave Area (dm ²)
Years	NS	NS	NS	*	*
S_I	106.6 $\pm$ 1.6 ^a	20.70 $\pm$ 0.56 ^a	5.5 $\pm$ 0.21 ^a	55.0 $\pm$ 2.4 ^b	156.1 $\pm$ 5.4 ^b
S_{II}	102.7 $\pm$ 1.5 ^a	22.1 $\pm$ 0.59 ^a	5.2 $\pm$ 0.22 ^b	62.4 $\pm$ 1.2 ^a	175.2 $\pm$ 2.5 ^a
Irrigation water applied (IWA)	**	**	**	**	**
$I_{100\%}$	110.6 $\pm$ 1.3 ^a	22.1 $\pm$ 0.91 ^a	5.6 $\pm$ 0.24 ^b	59.3 $\pm$ 1.8 ^a	169.1 $\pm$ 5.3 ^a
$I_{80\%}$	105.8 $\pm$ 1.4 ^b	20.9 $\pm$ 0.73 ^{a,b}	5.9 $\pm$ 0.07 ^a	60.4 $\pm$ 3.7 ^a	168.9 $\pm$ 7.0 ^a
$I_{60\%}$	97.5 $\pm$ 1.7 ^c	19.8 $\pm$ 0.53 ^b	4.5 $\pm$ 0.31 ^c	56.5 $\pm$ 1.2 ^b	169.1 $\pm$ 4.1 ^b
ACBio	**	**	**	**	**
$ACBio_0$	97.6 $\pm$ 1.6 ^c	19.6 $\pm$ 0.84 ^b	4.4 $\pm$ 0.33 ^c	51.4 $\pm$ 1.9 ^c	152.0 $\pm$ 6.8 ^c
$ACBio_5$	106.7 $\pm$ 1.3 ^b	21.4 $\pm$ 0.72 ^a	5.7 $\pm$ 0.18 ^b	58.0 $\pm$ 1.8 ^b	165.7 $\pm$ 3.8 ^b
$ACBio_{10}$	109.7 $\pm$ 1.7 ^a	21.8 $\pm$ 0.63 ^a	5.9 $\pm$ 0.07 ^a	66.8 $\pm$ 2.3 ^a	180.4 $\pm$ 3.5 ^a

** and * indicate respectively differences at $p \leq 0.05$ and $p \leq 0.01$ probability level, ns indicates not significant difference. Means followed by the same letter in each column are not significantly different according to the LSD test ($p < 0.05$).

Table 6. Mean square, F value, and probability for plant height, leaf number, branch number, dry matter, and leaf area.

Items	df	Mean Square					F Value and Probability				
		Plant Height (cm)	Leave No.	Branch No.	Dry Matter	Leave Area (dm ²)	Plant Height (cm)	Leave No.	Branch No.	Dry Matter	Leave Area (dm ²)
Season (S)	1	200.3	75.9	2.5	742.2	5329.31	50.4 ^{ns}	18.8 ^{ns}	28.1 ^{ns}	271.7 *	18.42 *
IWA	2	791.4	24.5	11.8	70.6	464.06	199.2 *	6.1 *	133.6 *	25.9 *	27.63 *
ACBio	2	716.1	25.9	9.2	1079.6	3623.95	180.3 *	6.4 *	103.5 *	395.2 *	44.23 *
S × IWA	2	11.5	17.9	0.09	178.9	854.82	2.9 ^{ns}	4.4 *	0.99 ^{ns}	65.0 *	50.89 *
S × ACBio	2	26.7	4.9	0.002	177.5	4582.64	6.7*	1.2 ^{ns}	0.02 ^{ns}	65.5 *	55.93 *
IWA × ACBio	4	15.3	27.8	8.1	327.6	581.04	3.8 *	6.9 *	91.5 *	119.9 *	7.09 *
S × IWA × ACBio	4	29.8	15.2	0.1	174.3	106.07	7.5 *	3.8 *	0.75 ^{ns}	63.8 *	1.29 ^{ns}
Exp. error	24	4.0	4.0	0.1	2.7	81.94					

ns: Nonsignificant. * Significant at the $p \leq 0.05$ level.

In this concern, [61,62] stated that biochar may improve the productivity of legume crops due to the increasing biological N₂ fixation. In general, our findings confirmed the potential effect of ACBio utilization in improving faba bean performance under abiotic stress. Various studies provided many hypotheses to indicate the influence of biochar addition on plant growth. In this context, [63] concluded that the use of biochar in some legumes crops increased shoot length, dry matter, nutrient concentration, and yield.

3.6. Water Productivity and Irrigation-Water Use Efficiency

Results presented in Table 7 and 8 reveal that WP and I-WUE were strongly affected by irrigation and ACBio treatments. On the other hand, the differences between growing seasons were significant for WP and non-significant for I-WUE. The WP and I-WUE's values were 11.9 and 15.6 for S_I, and 11.5 and 14.9 kg mm⁻¹ for S_{II} (Table 7). Likewise, the interactions between the irrigation regime and acidified biochar or between the irrigation regime, ACBio, and growing seasons were significantly affected (Table 8). Regarding the influence of IWA, results indicated that the values of WP and I-WUE were 10.5 and 14.2 for I_{100%}, 12.1 and 15.7 for I_{80%}, and 12.2 and 15.8 kg mm⁻¹ for I_{60%}, demonstrating that the WP and I-WUE for I_{60%} was higher by 15.2 and 10.6 than those of I_{80%} and by 16.2 and 11.3% for I_{100%}, respectively (Table 7). These outcomes are in concurrence with those of [11,64–69] who reported that I-WUE was not increased with increasing irrigation quantity for sorghum and melon.

Table 7. Means and standard errors for pod number, pod weight plant⁻¹, 100 seed weight, seed yield, water productivity (WP), and irrigation water use efficiency (I-WUE).

Items	Mean ± SE					
	Pods No. Plant ⁻¹	Pods Weight Plant ⁻¹ (g)	100 Seed Weight (g)	Seed Yield (t ha ⁻¹)	WP (kg mm ⁻¹)	I-WUE (Kg mm ⁻¹)
Years	NS	NS	NS	NS	NS	*
S _I	32.6 ± 1.00 a	127.8 ± 5.30 a	71.5 ± 1.6 a	3.7 ± 0.17 a	11.9 ± 0.05 a	15.6 ± 0.05 a
S _{II}	34.8 ± 1.30 a	124.1 ± 6.70 a	68.4 ± 1.6 a	3.7 ± 0.19 a	11.5 ± 0.05 a	14.9 ± 0.05 a
Irrigation water applied (IWA)	*	**	**	**	**	**
I _{100%}	34.7 ± 1.30 a	150.0 ± 5.70 a	71.2 ± 1.4 a	4.3 ± 0.22 a	10.5 ± 0.05 b	14.2 ± 0.05 b
I _{80%}	34.6 ± 1.70 a	132.8 ± 3.90 b	75.0 ± 2.0 a	4.1 ± 0.18 a	12.1 ± 0.05 a	15.7 ± 0.05 a
I _{60%}	31.7 ± 1.30 b	95.1 ± 5.20 c	63.6 ± 1.5 b	3.2 ± 0.16 b	12.2 ± 0.06 a	15.8 ± 0.06 a
ACBio	**	**	**	**	**	**
ACBio ₀	28.1 ± 0.88 c	104.3 ± 6.10 c	65.2 ± 2.0 b	2.7 ± 0.10 c	9.5 ± 0.01 c	12.3 ± 0.01 c
ACBio ₅	35.3 ± 1.28 b	128.7 ± 5.50 b	73.0 ± 1.4 a	3.9 ± 0.10 b	12.2 ± 0.03 b	15.8 ± 0.03 b
ACBio ₁₀	37.6 ± 1.12 a	144.8 ± 7.10 a	71.7 ± 1.9 a	4.4 ± 0.20 a	13.6 ± 0.03 a	17.7 ± 0.03 a

** and * indicate respectively differences at $p \leq 0.05$ and $p \leq 0.01$ probability level, ns indicates not significant difference. Means followed by the same letter in each column are not significantly different according to the LSD test ($p < 0.05$).

Table 8. Mean square, F value, and probability for pod number, pod weight plant^{−1}, 100 seed weight, seed yield, water productivity (WP), and irrigation water use efficiency (I-WUE).

Items	df	Mean Square						F Value and Probability					
		Pods No.	Pods Weight Plant ^{−1} (g)	100 Seed Weight (g)	Seed Yield (t ha ^{−1})	WP (kg mm ^{−1})	I-WUE (kg mm ^{−1})	Pods No.	Pods Weight Plant ^{−1} (g)	100 Seed Weight (g)	Seed Yield (t ha ^{−1})	WP (kg mm ^{−1})	I-WUE (kg mm ^{−1})
Season (S)	1	66.4	189.7	139.84	0.04	2.65	5.84	6.63 ^{ns}	5.02 ^{ns}	6.78 ^{ns}	0.78 ^{ns}	3.62 ^{ns}	4.8 *
IWA	2	54.0	14162.9	607.88	7.17	9.03	14.5	10.12 *	134.23 *	12.31 *	77.8 *	12.4 *	11.8 *
ACBio	2	448.4	7476.1	311.98	13.93	78.78	132.5	48.5 *	69.93 *	9.35 *	297.3 *	107.8 *	107.9 *
S × IWA	2	104.2	529.0	93.28	0.05	1.63	2.6	19.5 *	5.0 *	1.89 ^{ns}	0.6 ^{ns}	2.23 ^{ns}	2.1 ^{ns}
S × ACBio	2	16.1	12.3	71.41	0.03	0.01	0.01	1.74 ^{ns}	0.11 ^{ns}	2.14 ^{ns}	0.56 ^{ns}	0.01 ^{ns}	0.01 ^{ns}
IWA × ACBio	4	54.1	236.1	17.54	0.15	6.01	10.2	5.86 *	2.21 ^{ns}	0.53 ^{ns}	3.14 *	8.3 *	8.3 *
S × IWA × ACBio	4	48.9	503.1	6.84	0.27	2.6	4.4	5.3 *	4.71 *	0.20 ^{ns}	5.69 *	3.6 *	3.6 *
Exp. error	24	9.2	106.9	33.36	0.05	0.73	1.2						

ns: Nonsignificant. * Significant at the $p \leq 0.05$ level.

According to Figure 3, the correlation between IWA and I-WUE was curvilinear and the following equations indicate this relation:

$$\text{I-WUE} = -8 \times 10^{-5} \times \text{IWA}^2 + 0.0244 \times \text{IWA} + 14.97, R^2 = 0.781, \quad (5)$$

$$\text{I-WUE} = -0.0003 \times \text{IWA}^2 + 0.1284 \times \text{IWA} + 0.0889, R^2 = 0.652. \quad (6)$$

Results presented in Table 7 show that WP and I-WUE were influenced positively ($p \leq 0.05$) via the addition of ACBio. The maximum values of WP and I-WUE (13.6 and 17.7 kg mm^{−1}) were observed in ACBio₁₀ compared to 12.2 and 15.8 for ACBio₅ and 9.48 and 12.3 kg mm^{−1} for ACBio₀, respectively. By increasing the addition of ACBio from 0 to 5 and 10 t ha^{−1} of ACBio, WP values were increased by 28.7 and 43.5%, while I-WUE values were increased by 28.5 and 44%, respectively. Acidified biochar additions improve physico-chemical soil properties (Table 3) and mineral uptake (Table 4). Moreover, RACio improved water relations, as well as growth and yield relative to control (Tables 6 and 7). All of these factors are mainly responsible for improving WP and I-WUE. These findings are similar to those of [65,66].

Figure 3. Regression analysis between irrigation water applied (IWA), faba bean seed yield (SY), and irrigation-water use efficiency (I-WUE) in S_I (2016/17) and S_{II} (2017/18) seasons.

3.7. Faba Bean Seeds Yield

Pods number, pods weight, weight of 100 seeds, and seed yield (t ha^{-1}) were analyzed statistically and presented in Tables 7 and 8. They were positively influenced by IWA and ACBio rate and not affected by seasons ($p \leq 0.05$). Except for the pod number and weight of pods, no differences were observed for the interaction between irrigation and seasons (Table 8). Except for the pod number and seeds yield, the interaction between irrigation and ACBio for the aforementioned traits was not significant. The maximum seeds yield (4.9 and 5.5 t ha^{-1} for S_I and S_{II}) were observed when faba bean plants were

exposed to $I_{100\%}$ combined with 10 t ha^{-1} of ACBio. Conversely, the lowest seeds yield was recorded under severe irrigation conditions ($I_{60\%}$) without ACBio. Referring to the impact of irrigation regimes, findings showed that irrigated plants at $I_{100\%}$ increased faba bean seeds yield significantly followed by $I_{80\%}$ during both growing seasons. The highest yield was (4.33 t ha^{-1}) recorded when the faba bean received $I_{100\%}$ of ETc, whereas the lowest seeds yield was 3.16 t ha^{-1} observed under $I_{60\%}$ treatment (Table 7). A severe irrigation regime ($I_{60\%}$ of ETc) sharply reduced seeds yield by 37% and 30.4%, compared with $I_{100\%}$ and $I_{80\%}$ as an average for S_I and S_{II} , respectively. These findings may be due to the sufficient availability of soil moisture content, which leads to an increase in plant water status, physiological responses, increased activity of the microbial soil, improved nutrients uptake, and enhanced rates of photosynthesis, which may reflect on growth traits, pod number, pods weight, 100 seeds weight, and consequently higher yield. Similar outcomes were detected by [67,68]. Figure 3 shows the relationship between IWA and faba bean seed yield (SY) for S_I and S_{II} (polynomial of 2nd order). The relationship could be shown as follows:

$$SY = -6 \times 10^{-5} \times IWA^2 + 0.0372 \times IWA - 1.268, R^2 = 0.788, \quad (7)$$

$$SY = -7 \times 10^{-5} \times IWA^2 + 0.0511 \times IWA - 4.1705, R^2 = 0.96. \quad (8)$$

Regarding the impact of ACBio on the yield and quality of faba bean, data in Table 7 and 8 reflected that the highest yield was enlisted via the utilization of ACBio₁₀. Results showed that the utilization of ACBio₁₀ or ACBio₅ increased the yield of faba bean by 53.94 and 32.78% compared to ACBio₀. The effect of acidified biochar as a soil amendment on faba bean seeds yield was more significant under water stress. Similar findings were observed by [70–74]. Thus, merging deficit irrigation and acidified biochar could be the best strategy to increase the seeds yield of faba bean under water shortage. According to the analysis of ACBio (Table 2), it has a great organic carbon percentage, ash, macro and micronutrients, and cation exchange capacity (CEC). These ingredients enhance the acidified biochar in favor of the growing faba bean by modulating soil properties (hydro-physical, (i.e., total porosity, bulk density and field capacity) and chemical (i.e., ECe, pH, OM%, and macronutrients)). Moreover, the addition of ACBio increased the macronutrients (N, P, K, and Ca) concentration (Table 4) in faba bean plants. Subsequently, the content of nutrients will increase and easily uptake by growing faba bean plants, leading to an obvious increase in the growing and production of faba bean. This might be possibly interpreted by the positive role of ACBio on the soil properties; reduce soil pH, increase field capacity, total porosity, OM%, and nutrients uptake resulted in increasing the growth and productivity of faba bean.

4. Conclusions

Water restriction significantly reduced faba bean water status, physiological attributes, growth, and seeds yield of faba bean crop. Results showed that supplying ACBio was effective in modifying the adversative impacts of water scarcity through enhancing the quantum efficiency of a photosystem, water status, I-WUE, soil microbial activity, SPAD value, plant growth attributes, and improving soil properties. In this concern, ACBio could reduce bulk density, pH, ECe, and increase field capacity, soil macronutrients content (N, P, and K), and OM%. It could be stated that $I_{100} + \text{ACBio}_{10}$ was more suitable for obtaining the maximum seed yield in abiotic stress. Under limited water resources, a combination of $I_{80\%}$ and 10 t ha^{-1} ACBio is highly recommended to attain optimal seed yield with the opportunity of saving 20% of irrigation water during faba bean growing season.

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