doi:10.14720/aas.2024.120.4.19341 Original research article / izvirni znanstveni članek

Combined effects of deficit irrigation and biochar application on seed yield and its components in three different sesame varieties grown in sandy soil conditions

Mohamed Ali ABDELSATAR [1, 2], Mohamed A. EMAM [3], Ibrahim. M. ELARENY [1], Mohamed M. HASSONA [4], Ibthal S. EL-DEMARDASH [5]

Received July 17, 2024; accepted October 17, 2024.
Delo je prispelo 17. julij 2024, sprejeto 17. oktober 2024

Combined effects of deficit irrigation and biochar application on seed yield and its components in three different sesame varieties grown in sandy soil conditions

Abstract: To answer the question if biochar application was regarded as an effective tool for mitigating the adverse effects of drought stress on sesame production. Thus, two experiments were conducted in the summer season of 2023 and 2024 at Ismailia Agricultural Research Station, Egypt. A randomized complete block design in a split-plot arrangement with three replications was used for each irrigation regime. Biochar application rates were applied to the main plots, while sesame varieties were planted in the sub-plots. In the present study, deficit irrigation with biochar application improved the seed yield and its components significantly in all three sesame varieties. Combination of deficit irrigation with application of biochar proved to be a viable strategy to enhance productivity of sesame under sandy soils. In addition, application of biochar has been able to compensate for the negative deficit irrigation effects, resulting in higher seed yields.

Key words: biochar, seed yield and its components, sesame, varieties, drought stress

Kombinirani učinki uporabe biooglja in deficitnega namakanja na pridelek semena treh sort sezama in njegove komponente, rastočega v peščenih tleh

Izvleček: Raziskava je bila izvedena z namenom, da se ugotovi, če je uporaba biooglja učinkovito sredstvo za preprečevanje negativnih učinkov sušnega stresa na pridelek semena sezama. V ta namen sta bila izvedena dva poskusa v poletnih sezonah 2023 in 2024 na Ismailia Agricultural Research Station, Egypt. Popolni naključni bločni poskus z deljenkami s tremi ponovitvami je bil izveden za vsak način namakanja. Biooglje je bilo dodano na glavnih ploskvah, sorte sezama so bile posejane na podploskvah. Deficitno namakanje in uporaba biooglja sta značilno izboljšala pridelek semena in njegove komponenete pri vseh treh sortah sezama. Kombinacija deficitnega namakanja z uporabo biooglja se je izkazala kot dobra strategija za povečanje pridelka sezama na peščenih tleh. Dodatno je uporaba biooglja kompenzirala negativne učinke deficitnega namakanja, kar je omogočilo večje pridelke semena

Ključne besede: biooglje, pridelek semena in njegove komponenete, sezam, sorte, sušni stres

1 Oil Crops Research Department, Field Crops Research Institute, Agricultural Research Center, Giza, Egypt.
2 Corresponding author: Email: mohamedtemraz1@yahoo.com
3 Agronomy Department, Faculty of Agriculture, Suez Canal University, 41522 Ismailia, Egypt
4 Department of Sustainable Development of Environment and Its Projects Management, Environmental Studies & Research Institute (ESRI), University of Sadat City (USC), Six Zone, Sadat City, Menofiya, 22897, Egypt
5 Department of Genetics and Cytology, National Research Centre, Cairo, Egypt

1 INTRODUCTION

Sesame seeds are a rich source of essential nutrients, important vitamins, key minerals, and potent antioxidants that all play a very significant role in achieving a balanced diet. In the year 2022, Egyptian sesame seeds reached 48,000 tons harvested from 76,190 feddans, according to a 2022 report by FAO. The consumption of the sesame seeds, therefore, serves to reduce cholesterol levels and further limits inflammation of body organs by improving heart health. Besides, the rich content of calcium in sesame seeds greatly contributes to a strong skeleton and, therefore, is one of the possible healthy additions to a diverse diet. Zubair et al. (2020), Morya et al. (2022), and Sumara et al. (2023) all proved that regular sesame consumption favours cardiovascular and general health.

Drought stress manifested its effect in the form of reduction in biological yield, number of capsule per plant, and harvest index, which resulted in a net fall of 10.26 % in the biological yield of sesame plants. Surprisingly, the seed yield of sesame manifested no significant alteration due to drought stress. Although sesame is considered a drought-resistant crop, cases of drought stress may hamper its growth and reduce seed yield, affecting the components of yield, as found in works by Heidari et al. (2011) and Ebrahimian et al. (2019). Drought stress becomes a crucial factor, which reduces growth, seed yield and yield components in sesame plants. Even though sesame is considered to be relativelly drought-tolerant, under such conditions of the water-scarce regions, it still shows inhibitions in growth and yields, according to Ebrahimian et al. (2019). Also, according to studies by Hailu et al. (2018), large variations in the yield of sesame have been exposed concerning various deficit irrigation levels applied differently. Precisely, the treatments of 50 % ETc with alternate and conventional furrow application methods in both years of 2013 and 2015 had the highest averages. However, the highest yield was obtained from the 100 % ETc treatment under the conventional furrow application method. In another investigation, Qureshi et al. (2023) appraised the performance of 21 accessions collected from 12 different countries and exposed them to two different water-regime treatments, namely non-stressed (NS) and drought stress (DS). The results from the investigation showed a high variation in agronomic characteristics by the accessions. Surprisingly, the yield was the highest under the drought stressed treatment. Also, oil content and oleic acid were recorded at higher levels under the non-stressed treatment, hence giving very interesting findings from this study. Thus, promising genotypes are considered an important component of sustainable agricultural productivity and soil fertility management, especially in arid and semi-arid regions, which are facing the twin challenges of water scarcity and soil degradation. Such as Jabborova et al. (2023) and Ibrahim et al. (2013), biochar is a carbonaceous product produced by pyrolysis from organic materials that can be applied to improve physical and hydraulic conditions in soils for better plant growth with higher yields. Its application could result in savings on water by reducing evaporation losses and improving retention in coarse-textured sandy soils, improving soil quality and productivity with the reduction of irrigation water use without inhibiting crop yield, as suggested by Castellini et al. (2015). However, there was great variation in the impact that biochar had on the hydraulic properties of soils due to the wide variation in source materials, production conditions, soil composition, and experimental conditions in use within individual studies, as elaborated by Mukherjee and Lal (2013). This therefore found for the thorough assessment of the impacts of biochar on clayey soils for full realization of its benefits. Besides, biochar application has been found to increase crop yields, especially in sesame, through retention of water and nutrients in the soil. For this reason, the application of biochar in the case of sandy soil will reduce the problems of limited water by reducing evapotranspiration rates with increased retention of water. Thus, it becomes relevant to examine the potentiality of application of biochar to mitigate the effect of drought stress on seed yield and its attributes in three sesame cultivars that grow under sandy soil conditions. Therefore, the key objective of the present work was to examine if there is any probable impact of applying biochar on the mitigation of drought stress effects on seed yield and its various components using three different varieties of sesame grown under sandy soil conditions.

2 MATERIALS AND METHODS

2.1 SITE DESCRIPTION

Two experiments were carried out at the Ismailia Agricultural Research Station in Egypt during the summer seasons of 2023 and 2024. The geographical coordinates of the station are 30°35’ 41.9” N, 32°16’ 45.8” E, with an elevation of 3 meters above sea level. Prior to the planting phase, soil samples were carefully prepared by air-drying, finely grinding, sieving through a 2 mm sieve, and then stored for further analysis. The soil experiment included a detailed analysis of both physical and chemical parameters, which were documented and presented

Table 1: Physicals and chemicals analyses of experimental sites at 0-30 cm depth of soil.

.

Seasons	Available			pH	EC mmh/v	Clay %	Silt %	Fine sand %	Texture
	N	P	K						
2023	10.2	2.11	62	7.33	0.89	3.45	2.58	93.97	Sandy
2024	9.52	2.36	54	7.65	0.95	4.23	2.35	93.42	Sandy

in Table 1 according to Jackson (1973). In both seasons, the crop that was planted earlier was wheat.

2.1.1 Experimental design

For each irrigation regimes *i.e.,* mild (irrigation when 25 % of available soil moisture was depleted (ASMD), T1), moderately (irrigation when 50 % of ASMD, T2) and severe (irrigation when 75 % of ASMD, T3), the experiments were performed in a randomized complete block design (RCBD) using split-plot arrangement with three replications. The main plots received biochar application rates of B0, which represents zero addition and serves as the control; B10, which corresponds to an application rate of 10 (t ha^{-1}); and B20, which represents an application rate of 20 (t ha^{-1}), while sub-plots planted with three different sesame varieties: Shandaweel 3, Giza 32, and Sohag 1, as presented in Figure (1). The experimental unit area was 9 square meters, divided into five ridges with 60 centimeter widths and 3 meters lengths. Sesame varieties that underwent assessment were obtained from the Oil Crops Research Department, Field Crop Research Institute, Agricultural Research Center in Egypt.

2.2 CULTIVATING AND FIELD MANAGEMENT

The sesame varieties evaluated were sown manually on ridge at a spacing of 60 cm between ridges. The distance between hills was according to the variety recommendation. In both seasons, sowing date was on 15th April. Following the recommended guidelines, the sesame seedlings were thinned to maintain a plant density of one or two plants per hill. Besides that, all other agricultural practices and recommendations concerning the crop were carefully followed (Table 2).

2.3 DATA RECORDED

2.3.1 Yield and its component traits

The flowering date was taken for each experimental plot as a number of days taken to have 50 % of the plants within it start flowering. During the harvesting process, a selection of five competitive plants were chosen at random from both the 2nd and 4th ridges for the purpose of assessing seed yield and various attributes including plant height (in cm), fruiting zone length (in cm), number of branches per plant, 1000-seed mass (in grams), and seed mass per plant (in grams). The seed yield per square meter was determined by harvesting plants from central ridge units and converting them to kilograms per feddan.

2.4 STATISTICAL ANALYSIS

The study analyzed the mean values of three sesame varieties affected by different rates of biochar application for all studied traits in the three replications across three irrigation regimes and two seasons using a randomized

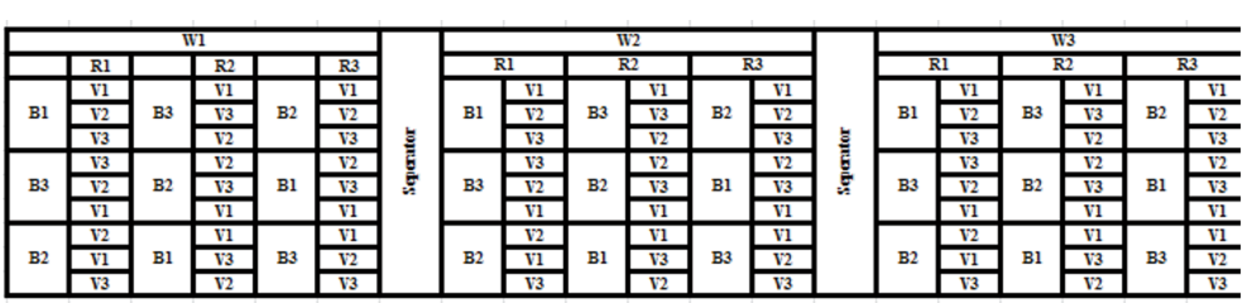

Figure 1: Scheme of Experimental design. W refers to water regimes; B refers to biochar application; V refers to varieties and R refers to replications

Table 2: Dates of planting, tillage, fertilizer, pesticides, and harvesting in the experiments conducted during two sesame seasons

Operation	Date	Date
Planting	15-April	15-April
Tillage application	05-Apr	04-Apr
Fertilizer Application	15 and 30 April	15 and 30 April
Pesticides application	05-May	06-May
Harvesting	01-Sep	01-Sep

complete block design using split-plot arrangement. At each water regime and season, bilateral and trilateral interactive effects were achieved through the combination of field experiments. These effects were further confirmed by the homogeneity of error variance, as stated by Gomez and Gomez (1984). The treatments were assessed by comparing their mean differences using the least significant difference (L.S.D. 5 %), as outlined by Gomez and Gomez (1984).

3 RESULTS AND DISCUSSION

3.1 ANALYSIS OF VARIANCES FOR ALL STUDIED TRAITS

The findings for the various studied traits of the three sesame varieties, which were evaluated in relation to the impact of biochar across different water regimes and seasons, can be found in Table 3. The combined analysis revealed that the main effect of year, as well as its dual and triple interactions with other factors, were found to be statistically insignificant for most studied traits. Consequently, these interactions were excluded from further analysis. In their place, the effects of the main effects of water regimes, biocahar rates, sesame genotypes, and their respective dual and triple interactions were examined. The combined analysis of variance showed that the main effects of water regimes, biochar, and sesame varieties on all the studied traits were highly significant, indicating that the main effect means much in the variation of studied traits. Additionally, for most of the studied traits, the dual interaction of water regimes and biochar rates was highly significant, indicating that the magnitude of the water regime effects varied significantly with varying biochar rate. Similarly, the combined analysis showed a highly significant interaction between water regimes and sesame varieties for all the traits, suggesting that the effect of water regimes on the traits varied significantly across different sesame varieties. In addition, as stated in the combined analysis, the dual influence of biochar and sesame varieties had a significant impact on all the traits that were studied. Similarly, the three-way interaction involving water regimes, biochar rates, and sesame varieties was highly significant for most of the traits, just like in the combined analysis. This meant that the studied water regimes influenced the studied characteristics being greatly dependent on the different biochar application rates, on one hand, and the investigated sesame varieties, on the other.

3.2 MAIN EFFECTS

3.2.1 Water regimes effects

Drought stress has been reported to inversely affect flowering stage of plants concerning 50 % flowering timing (Table 3). However, this treatment regime resulted in a reduction of 3.63 % and 12.89 % in the number of days required for 50 % flowering compared to treatments T2 and T1, respectively. Severe drought stress was found to delay flowering in sesame plants, which bears testimony to proper irrigation management in encouraging all growth parameters of sesame plants. This is further emphasized by the fact that the availability of water dictates the growth and development of these crops. Under water-scarce conditions, sesame plants manipulate the timing of flowering due to a regulation mechanism involved in the gene expression of the flowering pathway. Under drought stress conditions, some of the genes activated during the event of flowering are either overexpressed or suppressed, thereby advancing the onset of flowering. Other plant hormones such as abscisic acid and gibberellins have also been involved in the signaling and induction of early flowering under water-stress conditions. Plant height was considerably influenced by the water regimes. The tallest plants were observed in the well-watered treatment, while the shortest were those under the drought stress treatments (Table 4). However, surprisingly, it has been determined in this study that moderate levels of drought stress may be beneficial to obtain taller plants than by using the control treatment. The drought stress treatment was also responsible for the reduction of plant height by 1.68 % and 8.49 % compared to treatments T2 and T1, respectively. Silva et al. (2016), in their investigation, observed that the plants under the influence of drought stress developed highly reduced height compared to the plants, which had sufficient water supply. The retarded growth of sesame plants results from growth inhibition caused by limited

Table 3: Combined analysis of variance for three sesame varieties as affected by three rates of biochar across three water regimes and two years regarding all studied traits.

S.O.V	df		1st season	2nd season	Combined	1st season	2nd season	Combined
	Individual	Combined	Days to 50 % flowering			Plant height		
Year (Y)		1			83.06**			207.29*
Water regimes (W)	2	4	361.53**	300.48**	331.01**	1358.12**	1170.68**	1264.40**
Reps within W	6	12	0.50	0.42	1.45	1.42	1.95	3.88
Biochar (B)	2	2	159.27**	108.59**	265.19**	3453.58**	2747.33**	6179.11**
Y × B		2			2.67			21.80
W × B	4	8	11.35**	13.85**	12.60**	197.34**	219.39**	208.37**
Pooled error A	12	24	1.47	1.97	1.72	27.09	29.70	28.40
Varieties (V)	2	2	132.09**	71.26**	198.64**	1191.15**	1342.21**	2529.72**
Y × V		2			4.71			3.63
W × V	4	8	11.49**	9.63**	10.56**	113.25**	113.99**	113.62**
B × V	4	4	22.90**	16.91**	38.43**	308.80**	231.74**	533.36**
W × B × V	8	4	23.89**	13.97**	18.93**	101.02**	92.43**	96.72**
Y× B × V		16			1.3765			7.1804
Poled Error B	36	72	0.77	0.88	0.82	14.45	10.30	12.38
S.O.V	Individual	Combined	Fruiting zone length			Number of branches per plant		
Year (Y)		1			64.64**			19.36**
Water regimes (W)	2	4	149.83**	591.73**	370.78**	41.59**	44.90**	43.25**
Reps within W	6	12	0.69	1.27	1.66	0.17	0.70	0.55
Biochar (B)	2	2	2121.76**	1922.92**	4042.13**	12.70**	11.49**	24.02**
Y × B		2			2.54			0.17
W × B	4	8	32.31**	60.55**	46.43**	2.02**	3.31**	2.66**
Pooled error A	12	24	5.33	6.02	5.67	0.27	0.50	0.38
Varieties (V)	2	2	1223.03**	762.67**	1958.59**	107.70**	173.23**	277.06**
Y × V		2			27.12			3.88
W × V	4	8	45.14**	96.33**	70.74**	10.96**	14.66**	12.81**
B × V	4	4	158.49**	252.53**	370.92**	6.63**	6.53**	12.55**
W × B × V	8	4	57.34**	74.93**	66.14**	2.64**	2.96**	2.80**
Y× B × V		16			40.0890			0.6080
Poled Error B	36	72	5.18	5.31	5.25	0.38	0.64	0.51

*, ** Significant at 0.05 and 0.01 probability level, respectively

water availability, which impeded nutrient absorption and metabolic activity. This in turn will result in the ultimate reduction in photosynthesis and nutrient absorption, causing a plant to be short. The increased inhibition of root growth, prioritization towards root growth rather than shoot growth, and reduced cell elongation in shoots also favored the short height of the plants. Also, the plant can make hormones that save water by reducing its loss through transpiration. Water shortage clearly and negatively impacted the length of the fruiting zone of the sesame plants with a reduction of 4.82 % and 8.91 % as compared to T2 and T1, respectively (Table 4). This is in agreement with Abd El-Lattief (2015) findings that showed various irrigation regimes significantly affected plant height, fruiting zone length, branches, capsules, seed mass, and seed and oil yield. This indicates that drought stress adversely affected the fruiting zone length because of reduction in cell division and the rate of elongation contributing to short fruiting zones. This might be explained through resource allocation by the plant, whereby root development and seed production are favored over vegetative growth. Besides this, drought stress could cause hormonal changes which would ultimately result in a retardation of development of a well-thriving fruiting zone. Drought stress had an adverse impact on the number of branches per sesame plant, and it reduced these characteristics substantially compared to T2 and T1 by 43.65 and 108.00 %, respectively (Table 4). This is due to the serious water shortage that reduced water flow and caused an interruption of essential activities such as cell division, elongation, and differentiation. According to Pandey et al. (2021), drought stress interfered with the general growth and development of the plants; this interfered with dry mass and reduced plant yield, as reported by Askari et al. (2018). According to Table 4, drought stress significantly and adversely affected the 1000-seed mass. In comparison to T2 and T1, under drought stress, there was a reduction of 0.79 % and 8.93 %, respectively, in 1000-seed mass. The decrease in 1000-seed mass was caused by the reduced rate of photosynthesis and carbon assimilation due to water stress. Because water was limited, photosynthesis, being an efficient one, was restricted,

Table 3: Continued

S.O.V	df		1st season	2nd season	Combined	1st season	2nd season	Combined
	Individual	Combined	1000-seed mass			Seed mass per plant		
Year (Y)		1			0.99**			29.11**
Water regimes (W)	2	4	0.44**	1.17**	0.81**	2417.69**	2402.02**	2409.86**
Reps within W	6	12	0.02	0.003	0.01	0.98	1.38	1.64
Biochar (B)	2	2	3.67**	2.66**	6.30**	42.84**	53.26**	95.81**
Y × B	0	2			0.04			0.29
W × B	4	8	0.05*	0.08*	0.07**	4.49*	9.21**	6.85**
Pooled error A	12	24	0.01	0.02	0.01	0.84	0.87	0.85
Varieties (V)	2	2	1.73**	0.84**	2.48**	91.86**	79.02**	170.38**
Y × V	0	2			0.08			0.50
W × V	4	8	0.05**	0.14**	0.10**	6.96**	7.82**	7.39**
B × V	4	4	0.11**	0.06*	0.14**	8.40**	6.94**	13.05**
W × B × V	8	4	0.05**	0.15**	0.10**	1.83NS	8.62**	5.22**
Y× B × V	0	16			0.0258			2.2913
Poled Error B	36	72	0.01	0.02	0.01	1.41	0.95	1.18
S.O.V	Individual	Combined	Seed yield per feddan			Seed oil content		
Year (Y)		1			8320.64**			1.71NS
Water regimes (W)	2	4	867786.02**	943556.53**	905671.28**	31.76**	45.29**	38.53**
Reps within W	6	12	56.35	88.91	81.27	0.42	0.59	0.70
Biochar (B)	2	2	12214.47**	17757.93**	29711.77**	107.36**	72.19**	177.46**
Y × B	0	2			260.62			2.08
W × B	4	8	1580.74**	3939.52**	2760.13**	1.82NS	7.30**	4.56**
Pooled error a	12	24	130.64	304.35	217.49	0.67	0.94	0.81
Varieties (V)	2	2	35326.95**	26510.58**	61519.90**	75.69**	49.55**	122.38**
Y × V	0	2			317.63			2.86
W × V	4	8	2668.60**	3344.10**	3006.35**	2.62**	3.26*	2.94**
B × V	4	4	3276.85**	2032.26**	4067.51**	3.51**	7.07**	9.94**
W × B × V	8	4	383.49*	3231.74**	1807.62**	1.29NS	3.72**	2.51**
Y× B × V	0	16			1241.6043			0.6377
Poled Error B	36	72	152.83	121.52	137.17	0.61	0.93	0.77

*, ** Significant at 0.05 and 0.01 probability level, respectively

and hence the seeds were smaller in size and mass. The closing of the stomata restricts the intake of carbon dioxide, hence again affecting the size and mass of the seeds. In addition to that, drought stress disrupted nutrient uptake and transport, adding to the detrimental effects on mass. All these combined to reduce 1000-seed mass in the sesame plants that were exposed to drought stress.

Drought stress significantly and adversely affected seed yield per plant, which was reduced by 45.65 and 164.23 % in comparison with T2 and T1, respectively (Table 4). Such a reduction in seed yield may be due to the harmful influence of drought stress on the metabolism of sesame plants, which affected photosynthesis negatively because of the lack of appropriate water supply. As a result, the seed production and filling reduced, which resulted in reduced flowering and seed setting. Moreover, the drought stress thwarted the photosynthetic rate to lower the capacity of carbon dioxide absorption by the plant for carrying out photosynthesis. Besides, the scanty water further reduced nutrient uptake and its availability, which altogether made the plant inefficient in producing seeds. Drought stress showed the significant negative effect on reducing seed yield per feddan by 48.62 % and 173.12 % compared to T2 and T1, respectively, given in Table 4. This is due to the decline of photosynthesis and nutrient absorption reflected in smaller-sized and weighted seeds. Moreover, drought stress decreases the plant's capability for setting and retaining capsules; this contributed to the reduction of seed yield. Furthermore, the sizes and mass of individual seeds are reduced by drought stress, adding to the overall depression of seed yield per feddan. Water deficiency significantly increased the content of seed oil by 2.16 % and 5.25 % over T2 and T1, respectively (Table 4). This could be due to the action of drought stress on the sesame plants via positive regulation of key genes associated with biosynthesis of oil, lipid biosynthesis, and stress-responsive pathways. Consequently, these genes trigger, and oil production increases in the seed by enhanced accumulation of storage lipid. Further, the stress-responsive pathway increased antioxidant production, improved the expression of the oil biosynthesis genes that enable plants to retain more oil in their seeds to improve yield and quality. Similar results was reported by Abdo and Anton (2009) their study was conducted at Ismailia Agricultural Research Station to study the physiological response of sesame 'Shandaweel-3' to three levels of soil moisture depletion (ASMD): wet (20-25 %), medium (45-50 %), and dry (65-70 %). Results showed that increasing soil moisture stress significantly decreased plant height, and fruiting zone length. Dry treatment reduced 1000-seed mass, number of capsules, seed mass/plant, seed yields/fed and oil contents in seeds. Moreover, Askari, et al (2019) showed that drought stress reduced seed yield and its components.

3.2.2 Biochar application effect

Application of biochar at different levels ranging from zero to 10 up to 20 t ha^{-1} resulted in a gradual increase in all the studied traits, as shown in Table 4. Specifically, when comparing the non-application of biochar, the application of 10 and 20 t ha^{-1} led to significant increases in the following studied traits: days to 50 % flowering by 1.31 % and 7.53 %, plant height by 10.99 % and 13.58 %, fruiting zone length by 13.01 % and 24.26 %, number of branches per plant by 4.88 % and 40.24 %, 1000-seed mass by 8.04 % and 20.73 %, seed mass per plant by 8.02 % and 13.57 %, seed yield per feddan by 7.26 % and 12.70 %, and seed oil content by 3.23 % and 8.54 %, respectively. The above improvement may be attributed to the fact that biochar had a positive effect on soil fertility and nutrient availability in the plants, hence improving growth and development. It improved water and nutrient retention, reduced acidity in the soil by improving microbial activities. This sustainable method, therefore, improved sesame crop yield and quality but also sustained healthier plants with minimal environmental stress. Besides, biochar increased nutrient availability, advanced the plants toward early flower, enhanced plant height, and thus resulted in a higher yield of seeds per

Table 4: The main effect of water regimes on seed yield and its components as combined analysis across the studied sesame varieties, biochar application rates and the two seasons

Traits/ Water regimes	Days to 50 % flowering (N0)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant (N0)	1000-seed mass(g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
25 % of ASMD	59.69	165.71	83.69	4.81	3.69	30.40	577.65	42.60
50 % of ASMD	57.59	162.98	79.85	3.35	3.66	20.87	388.68	43.54
75 % of ASMD	52.87	152.74	76.85	2.31	3.39	11.50	211.50	44.96
LSD 0.05	0.52	2.99	1.34	0.35	0.07	0.52	8.28	0.50

ASMD refers to available soil moisture depleted feddan. The favorable impact of biochar on productivity also appeared in the case of sesame plants concerning the 1000-seed mass and the oil content of seeds. Wacal et al. (2019) also announced similar findings while investigating the effect of adding biochar on sesame performance regarding growth and yield, leaf nutrient concentration, seed mineral nutrients, and some soil physicochemical properties. Their results showed that biochar addition increased plant height, yield, and seed number.

3.2.3 Sesame varieties effects

The performance of different sesame varieties varied significantly in terms of all studied traits, as shown

Table 5: The main effect of biochar application rates on seed yield and its components, as combined analysis across the studied sesame varieties, water regimes and the two seasons

Traits/ Biochar application rates	Days to 50 % flowering (N0)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant (N0)	1000-seed mass (g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
B 0 (t ha^{-1})	55.09	148.33	71.27	3.04	3.27	19.52	368.12	42.05
B20 (t ha^{-1})	55.81	164.63	80.55	3.19	3.53	21.08	394.84	43.41
B20 (t ha^{-1})	59.24	168.48	88.56	4.26	3.94	22.17	414.88	45.64
LSD 0.05	0.52	2.99	1.34	0.35	0.07	0.52	8.28	0.50

Table 6: Agronomic performance of tested sesame varieties, as combined analysis across biochar application rates, water regimes and the two seasons

Traits/ Sesame varieties	Days to 50% flowering (N0)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant (N0)	1000-seed mass (g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
Shandaweel 3	58.15	165.98	86.11	0.89	3.82	22.74	425.93	45.30
Giza 32	57.46	162.64	80.21	5.00	3.52	20.85	393.47	43.48
Sohag 1	54.54	152.81	74.06	4.59	3.40	19.19	358.44	42.32
LSD 0.05	0.35	1.91	1.24	0.39	0.06	0.59	6.35	0.48

Table 7: The dual interactive of water regimes with biochar application rates on seed yield and its components, as combined analysis across the studied sesame varieties, and the two seasons

Interaction	Traits	Days to 50% flowering (N0)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant (N0)	1000-seed mass (g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
25 % of ASMD	B 0 (ton ha^{-1})	57.39	153.84	74.14	4.06	3.30	28.09	534.31	40.64
	B20 (ton ha^{-1})	58.89	166.99	82.48	4.22	3.71	30.71	583.69	42.04
	B20 (ton ha^{-1})	62.78	176.31	94.45	6.17	4.06	32.39	614.97	45.12
50 % of ASMD	B 0 (ton ha^{-1})	55.67	148.45	72.14	2.89	3.34	19.76	370.84	42.02
	B20 (ton ha^{-1})	57.83	166.09	81.66	3.00	3.62	20.64	384.09	43.03
	B20 (ton ha^{-1})	59.28	174.39	85.74	4.17	4.02	22.20	411.11	45.58
75 % of ASMD	B 0 (ton ha^{-1})	52.22	142.69	67.54	2.17	3.16	10.71	199.22	43.50
	B20 (ton ha^{-1})	50.72	160.80	77.50	2.33	3.26	11.90	216.73	45.16
	B20 (ton ha^{-1})	55.67	154.73	85.50	2.44	3.75	11.91	218.56	46.23
LSD0.05		0.90	5.18	2.32	0.60	0.11	0.90	14.35	0.87

ASMD refers to available soil moisture depleted, and B refers to biochar rates in Table 6. Among these varieties, 'Sohag1' had the shortest period to 50 % flowering, with a duration of 54.54 days, compared to the other varieties. 'Giza 32' and 'Shandaweel 3' demonstrated superiority over 'Sohag 1' in plant height by 8.62 % and 6.43 %, respectively. In addition, 'Shandaweel 3' and 'Giza 32' surpassed 'Sohag 1' in all the other studied traits, viz., length of fruiting zone, mass of 1000 seeds, mass of seed per plant, yield per feddan, and seed oil content. The percentage difference between the best and 'Sohag 1' varied between 3.58 % and 18.83 %. However, 'Shandaweel 3' had the lowest number of branches per plant in the comparison to others. Probably, differences in means for seed yield and its components that exist in sesame varieties Shandaweel 3, Giza 32, and Sohag1 may be described by diversity in the genetic structure of these cultivars. In other words, the genetic features associated with the variety would be major factors

Table 8: The dual interactive of water regimes with studied sesame varieties on seed yield and its components, as combined analysis across biochar application rates, and two seasons

Interaction	Traits	Days to 50% flowering (N0)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant (N0)	1000-seed mass (g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
	Shandaweel 3	61.94	169.25	87.60	0.94	3.95	32.27	611.52	44.44
25 % of ASMD	Giza 32	59.22	170.14	86.34	6.78	3.62	30.93	592.43	42.39
	Sohag 1	57.89	157.75	77.13	6.72	3.50	27.99	529.01	40.97
	Shandaweel 3	58.06	166.72	88.56	0.89	3.89	22.99	429.01	45.20
50 % of ASMD	Giza 32	59.44	167.23	77.82	4.33	3.69	20.81	387.54	43.61
	Sohag 1	55.28	154.98	73.17	4.83	3.40	18.81	349.50	41.82
	Shandaweel 3	54.44	161.96	82.17	0.83	3.61	12.95	237.26	46.27
75 % of ASMD	Giza 32	53.72	150.55	76.48	3.89	3.26	10.80	200.44	44.46
	Sohag 1	50.44	145.71	71.89	2.22	3.30	10.77	196.81	44.16
LSD0.05		0.60	3.31	2.15	0.67	0.11	1.02	11.01	0.83

ASMD refers to available soil moisture depleted

Table 9: The dual interactive of biochar application rates with studied sesame varieties on seed yield and its components, as combined analysis across water regimes, and two seasons

Interaction	Traits	Days to 50 % flowering (N0)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant (N0)	1000-seed mass (g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
	Shandaweel 3	55.06	153.05	80.09	0.89	3.47	20.82	395.65	43.59
B 0 (t ha^{-1})	Giza 32	56.06	148.72	68.77	4.61	3.25	18.89	355.88	41.66
	Sohag 1	54.17	143.21	64.96	3.61	3.08	18.85	352.83	40.90
	Shandaweel 3	57.11	169.89	85.59	0.83	3.69	22.89	427.26	45.78
B20 (t ha^{-1})	Giza 32	56.50	162.94	85.55	5.00	3.51	21.22	401.99	43.24
	Sohag 1	53.83	161.06	70.51	3.72	3.39	19.14	355.26	41.21
	Shandaweel 3	62.28	175.00	92.65	0.94	4.29	24.50	454.87	46.54
B20 (t ha^{-1})	Giza 32	59.83	176.26	86.31	5.39	3.81	22.43	422.54	45.55
	Sohag 1	55.61	154.17	86.72	6.44	3.73	19.58	367.23	44.84
LSD0.05		0.60	3.31	2.15	0.67	0.11	1.02	11.01	0.83

B refers to biochar rates

that will determine the varieties' overall productivity regarding flowering time, the number of capsules per plant, and size of seeds. Nevertheless, it is important to emphasize that environmental conditions and farming practices have a contribution to making the final seed yield. Among them, 'Shandaweel 3' showed higher productivity due to an efficient system of nutrient absorption and transfer inside the plant. It might be because of the breeding selection and genetic modification done through the years to focus on these traits. This could encourage farmers to buy seeds like 'Shandaweel 3', as they end up with a far more rewarding harvest than with other varieties, such as Giza 32 and Sohag 1. Its success with 'Shandaweel 3' in terms of yield and quality of the seeds proved that research and development was truly significant in enhancing crop varieties toward sustainable agriculture. The same trends were reported by Abdelsatar et al. (2021), who recorded significant differences in the performance of three sesame varieties, Giza 32, Sohag 1, and Shandaweel 3, based on seed yield and its components.

Table 10: Effect of triple interaction among water regimes, biochar application rates and sesame varieties on all studied traits as combined analysis across two seasons

Interaction	Traits		Days to 50% flowering (day)	Plant height (cm)	Fruiting zone length (cm)	Number of branches per plant	1000-seed mass (g)	Seed mass per plant (g)	Seed yield per feddan (kg)	Seed oil content (%)
25 % of ASMD	B 0 (ton ha^{-1})	Shandaweel 3	57.33	158.10	80.04	0.83	3.45	28.74	548.44	42.04
		Giza 32	58.00	152.44	74.37	5.50	3.24	29.58	561.69	40.39
		Sohag 1	56.83	150.97	68.02	5.83	3.22	25.94	492.79	39.50
	B20 (ton ha^{-1})	Shandaweel 3	61.00	171.46	82.35	0.83	4.06	32.65	622.05	44.28
		Giza 32	58.50	168.58	91.16	7.33	3.62	30.90	594.79	41.76
		Sohag 1	57.17	160.94	73.94	4.50	3.47	28.59	534.23	40.10
	B20 (ton ha^{-1})	Shandaweel 3	67.50	178.19	100.40	1.17	4.36	35.43	664.07	47.02
		Giza 32	61.17	189.40	93.50	7.50	4.00	32.32	620.81	45.02
		Sohag 1	59.67	161.34	89.45	9.83	3.82	29.44	560.02	43.32
50 % of ASMD	B 0 (ton ha^{-1})	Shandaweel 3	55.83	152.82	82.17	0.67	3.52	21.79	413.76	43.50
		Giza 32	56.33	148.71	70.09	4.83	3.45	18.32	338.82	42.16
		Sohag 1	54.83	143.82	64.16	3.17	3.06	19.19	359.95	40.39
	B20 (ton ha^{-1})	Shandaweel 3	57.67	170.19	91.17	0.83	3.79	22.98	423.70	45.27
		Giza 32	62.33	164.11	82.32	3.50	3.58	20.68	389.16	43.06
		Sohag 1	53.50	163.98	71.50	4.67	3.49	18.26	339.41	40.76
	B20 (t ha^{-1})	Shandaweel 3	60.67	177.17	92.33	1.17	4.37	24.21	449.55	46.84
		Giza 32	59.67	188.87	81.04	4.67	4.05	23.43	434.64	45.61
		Sohag 1	57.50	157.14	83.84	6.67	3.65	18.97	349.13	44.30
75 % of ASMD	B 0 (t ha^{-1})	Shandaweel 3	52.00	148.24	78.05	1.17	3.44	11.94	224.76	45.24
		Giza 32	53.83	145.00	61.86	3.50	3.05	8.77	167.13	42.43
		Sohag 1	50.83	134.83	62.71	1.83	2.97	11.42	205.77	42.82
	B20 (t ha^{-1})	Shandaweel 3	52.67	168.00	83.25	0.83	3.23	13.05	236.03	47.80
		Giza 32	48.67	156.14	83.16	4.17	3.35	12.09	222.02	44.91
		Sohag 1	50.83	158.26	66.09	2.00	3.20	10.56	192.13	42.76
	B20 (t ha^{-1})	Shandaweel 3	58.67	169.65	85.22	0.50	4.15	13.86	250.99	45.76
		Giza 32	58.67	150.51	84.41	4.00	3.37	11.53	212.17	46.03
		Sohag 1	49.67	144.04	86.88	2.83	3.73	10.33	192.53	46.89
LSD 0.05			1.04	5.73	3.73	1.17	0.19	1.77	19.06	1.43

ASMD refers to available soil moisture depleted, and B refers to biochar rates

3.3 DUAL AND TRIPLE INTERACTIONS EFFECTS ON STUDIED TRAITS

The combined effect of water regimes and biochar application significantly impacted the performance of the traits under study (Table 3 and 6). The highest values for these traits were recorded when biochar was applied at a rate of 20 t ha^{-1} under normal irrigation conditions. Also, increased application rates of biochar under the different water regimes continued to improve the performance of the studied traits in the betterment in plants' ability to tolerate the water stress conditions studied. As evident from Table 3 and 8, the interactions of dual water regimes significantly influenced various investigated trait performances in the tested varieties. Maximum values for most of the investigated traits were recorded when 'Shandaweel 3' was planted under a normal irrigation conditions. Unexpectedly, the best performance was shown by 'Shandaweel 3' variety when sown under both moderate and severe levels of water stress over other varieties. This may partly be due to the great capability of its adaptation to unfavorable conditions such as drought stress. Numerous studies had demonstrated that the growth of the shoot system could be influenced either positively or negatively by changes in water scarcity, soil type, and plant species. Decrease in plant growth under high drought stress levels may be due to inhibition in hydrolysis of reserved food and its translocation to the growing shoots.

It showed from the research that there was a significant and positive interaction between biochar application and sesame varieties in all the studied traits reflected from Table 3 and 9. Maximum values of most of these traits were exhibited while using Shandaweel 3 variety followed by Giza 32 and Sohag 1 varieties. Additionally, these positive effects were observed with increasing levels of biochar application, up to 20 tons per hectare.

In addition, the combination of water regimes and biochar application with different sesame genotypes had a significant impact on all studied traits (Table 3 and 10). This presents an opportunity to identify the most favorable triple interactions for these traits. Based on this perspective, the most favorable triple interaction was observed when 'Shandaweel 3' was sown under normal irrigation and biochar was applied at a rate of 20 tons per hectare. Furthermore, 'Shandaweel 3' outperformed other varieties, even when it was sown under different water regimes with the highest application rate of biochar at 20 tons per hectare.

4 CONCLUSION

It can be concluded that investigated deficit irrigation and application of biochar on seed yield and its components in three diverse varieties of sesame grown under a sandy soil environment, thus providing realistic overviews of the methods to be used for sustainable agricultural practices that would enable farmers to have maximum yields in water-scarce regions. 'Shandaweel 3' was more tolerant and adaptable to a wide range of environmental conditions compared to the other varieties. The results of this study clearly indicate the potentiality for a positive role of biochar treatment in agricultural practice, both to improve the performance in crops and to enhance tolerance against drought stress. 'Shandaweel 3' demonstrated the most favorable triple interaction when sown with a biochar rate of 20 tons per hectare in water-limiting environments. More studies are recommended in order to explain, in full, the mechanisms responsible for such improvements and, secondly, to optimize biochar application rates in view of crop varieties. In a nutshell, the results obtained from this study provided meaningful insight into how farmers and practitioners may work to improve sesame productivity in a water-limiting environment.

5 REFERENCES

Abd El-Lattief, E. A. (2015). Impact of irrigation intervals on productivity of sesame under southern Egypt conditions. *International Journal of Advanced Research in Engineering and Applied Sciences*, *4*(10), 1-9.

Abdelsatar, M. A., Elmasry, H. M., & Attia, M. A. (2021). Role of potassium fertilizer in improving yield and its components for some sesame varieties under salt-affected soil conditions. *SVU-International Journal of Agricultural Sciences*, *3*(1), 18-30.

Abdo, F. A., & Anton, N. A. (2009). Physiological response of sesame to soil moisture stress and potassium fertilization in sandy soil. *Fayoum Journal of Agricultural Research and Development*, *23*(1), 88-111.

Askari, A., Ardakani, M. R., Paknejad, F., & Hosseini, Y. (2019). Effects of mycorrhizal symbiosis and seed priming on yield and water use efficiency of sesame under drought stress condition. *Scientia Horticulturae*, *257*, 108749.

Askari, A., Ardakani, M. R., Vazan, S., Paknejad, F., & Hosseini, Y. (2018). The effect of mycorrhizal symbiosis and seed priming on the amount of chlorophyll index and absorption of nutrients under drought stress in sesame plant under field conditions. *Applied Ecology & Environmental Research*, *16*(1), 335-357.

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., & Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research*, *154*, 1-13.

Ebrahimian, E., Seyyedi, S. M., Bybordi, A., & Damalas, C. A. (2019). Seed yield and oil quality of sunflower, safflower, and sesame under different levels of irrigation water availability. *Agricultural Water Management*, *218*, 149-157.

Filiberto, D. M., & Gaunt, J. L. (2013). Practicality of biochar additions to enhance soil and crop productivity. *Agriculture, 3*(4), 715-725.

Gholamhoseini, M. (2020). Evaluation of sesame genotypes for agronomic traits and stress indices grown under different irrigation treatments. *Agronomy Journal, 112*(3), 1794-1804.

Gomez, K.A., and Gomez, A.A. (1984). '*Statistical Procedures for Agricultural Research'*, 2nd Ed. New York: John Willey and Sons Inc.

Hailu, E. K., Urga, Y. D., Sori, N. A., Borona, F. R., & Tufa, K. N. (2018). Sesame yield response to deficit irrigation and water application techniques in irrigated agriculture, Ethiopia. *International Journal of Agronomy,* (1), 5084056.

Heidari, M., Galavi, M., & Hassani, M. (2011). Effect of sulfur and iron fertilizers on yield, yield components and nutrient uptake in sesame (*Sesamum indicum* L.) under water stress. *African Journal of Biotechnology, 10*(44), 8816-8822.

Ibrahim, H. M., Al-Wabel, M. I., Usman, A. R., & Al-Omran, A. (2013). Effect of *Conocarpus* biochar application on the hydraulic properties of a sandy loam soil. *Soil science, 178*(4), 165-173.

Jabborova, D., Abdrakhmanov, T., Jabbarov, Z., Abdullaev, S., Azimov, A., Mohamed, I., ... & Elkelish, A. (2023). Biochar improves the growth and physiological traits of alfalfa, amaranth and maize grown under salt stress. *Peer J, 1*, e15684.

Morya, S., Menaa, F., Jiménez-López, C., Lourenço-Lopes, C., BinMowyna, M. N., & Alqahtani, A. (2022). Nutraceutical and pharmaceutical behavior of bioactive compounds of miracle oilseeds: An overview. *Foods, 11*(13), 1824.

Mukherjee, A., & Lal, R. (2013). Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy, 3*(2), 313-339.

Pandey, B. B., Ratnakumar, P. B. U. K., Usha Kiran, B., Dudhe, M. Y., Lakshmi, G. S., Ramesh, K., & Guhey, A. (2021). Identifying traits associated with terminal drought tolerance in sesame (*Sesamum indicum* L.) genotypes. *Frontiers in Plant Science, 12*, 739896.

Quilliam, R. S., Marsden, K. A., Gertler, C., Rousk, J., DeLuca, T. H., & Jones, D. L. (2012). Nutrient dynamics, microbial growth and weed emergence in biochar amended soil are influenced by time since application and reapplication rate. *Agriculture, Ecosystems & Environment, 158*, 192-199.

Qureshi, M., Arslan, M., Golukcu, M., Bera, S. K., Uzun, B., & Yol, E. (2023). Assessment of drought tolerance of sesame germplasm with agronomic and quality traits. *Crop Science, 63*(5), 2763-2777.

Silva, R. T. D., Oliveira, A. B. D., Lopes, M. D. F. D. Q., Guimarães, M. D. A., & Dutra, A. S. (2016). Physiological quality of sesame seeds produced from plants subjected to water stress. *Revista Ciência Agronômica, 47*, 643-648.

Sumara, A., Stachniuk, A., Montowska, M., Kotecka-Majchrzak, K., Grywalska, E., Mitura, P., ... & Fornal, E. (2023). Comprehensive review of seven plant seed oils: chemical composition, nutritional properties, and biomedical functions. *Food Reviews International, 39*(8), 5402-5422.

Wacal, C., Ogata, N., Basalirwa, D., Handa, T., Sasagawa, D., Acidri, R., ... & Nishihara, E. (2019). Growth, seed yield, mineral nutrients and soil properties of sesame (*Sesamum indicum* L.) as influenced by biochar addition on upland field converted from paddy. *Agronomy, 9*(2), 55.

Zubair, A. B., Maxwell, Y. M. O., Femi, F. A., Azeez, S. O., Jiya, M. J., & Owheruo, J. O. (2020). Proximate, mineral and functional properties of maize starch complemented with defatted sesame seed flour. *Anchor University Journal of Science and Technology (AUJST), 1*(1), 61-67.