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Improving the growth parameters, yield, and oil quality of camelina in rainfed farming due to the combined use of biochar and supplementary irrigation

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ABSTRACT

The main concerns for agricultural production nowadays are excessive crop cultivation, water scarcity, and poor soil quality. It is possible to amend agronomic soil with activated biochar (BC) to achieve high water-fertilizer availability and Camelina crop production under rainfed conditions by using an efficient and environmentally safe technology. A split plot experiment was arranged on a randomized complete block design with nine treatments and three replications. The main and second factors were supplementary irrigation (SI) and BC, respectively, with SI comprising of no irrigation (control), irrigation at the flowering stage and seed-filling stage, while BC included control (BC0), 5 (BC5), and 10 (BC10) t ha^{-1}. The number of lateral branches and seeds in the silique, seed yield (2751.8 kg ha^{-1}), 1000-seed weight (1.16 g) and oil yield (991.50 kg ha^{-1}) were highest in response to irrigation at the flowering stage and the application of BC10. The gas chromatography analysis showed that the highest amount of unsaturated fatty acids (oleic, linoleic, linolenic, eicosadienoic and palmitic acids) was obtained in response to BC10 and irrigation at the seed-filling stage. Finally, the results showed that BC10 and the application of SI at the flowering stage increased the seed and oil yield, and unsaturated fatty acid content in Camelina. This study demonstrates that BC amendments can improve plant performance and preserve the environment, with significant implications for the alleviation of drought and sustainable Camelina production in arid regions. The study provides a practical way to produce Camelina in rainfed areas, which can benefit farmers economically.

1. Introduction

False flax, or *Camelina sativa* L., is a member of the Brassicaceae family and is an oilseed crop that has been gaining increasing interest due to its unique agronomic properties and its potential for use in various industries [1]. While camelina was cultivated in Europe as a source of edible oil and folk medicine since the 1950s, it was eventually replaced by more productive oilseed crops [2]. However, with recent advancements in technology, camelina oil has re-emerged as a renewable vegetable oil that can be used in biofuel production and as biological raw materials.

Camelina has become a popular crop due to its superior agronomic properties, which confer many advantages over other oilseed crops. Camelina seeds contain approximately 30–40 % oil, making it a valuable source for both industrial and nutritional applications [3]. Additionally, camelina establishes a balance of unsaturated fatty acids (UFAs) in human diets that are highly stable in oxidative terms [4]. It also has smaller amounts of saturated fatty acids, making it suitable for human diets [5]. The fatty acids found in camelina oil include oleic (14–16 %), linoleic (15–23 %), α-linolenic (31–40 %), eicosenoic acid (12–15 %), and other minor fatty acids, including palmitic, stearic, and erucic acid [6].

One of the reasons for camelina's recent popularity is its low agricultural input requirement, tolerance to cold and drought climates, and resistance to diseases that are common to oilseed Brassica crops [7]. These characteristics make it a valuable addition to environmentally friendly agricultural practices. Therefore, camelina is an attractive alternative to other oilseed crops, and its cultivation can benefit farmers

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and industries alike.

Camelina is a versatile crop that can flourish under a variety of environmental conditions, including limited water availability, high and low temperatures, and various types of stress. In particular, camelina has the potential to thrive in marginal and poor lands in the Middle East and Mediterranean regions, where other high-value crops may not be economically feasible [8]. As a short-season species with both spring and autumn forms, camelina provides numerous ecological benefits as an annual winter and spring crop. These benefits include protection against soil erosion, prevention of nitrate run-off, weed control, and provision of pollinator feed [6,9,10].

Given that the global population is expected to surpass 10 billion people by 2050, factors like climate change pose significant threats to food safety. Abiotic stressors like drought, extreme temperatures, and salty soils have reduced the productivity of staple crops, putting food and nutritional security at risk [11].

Increasing global food production will require expanding cultivated lands, which can be accomplished by intensifying current resources for cultivation or developing integrated management methods. However, a major challenge to sustainability in agriculture is the lack of water resources, especially in arid and semi-arid areas. Water scarcity is a major constraining factor that greatly impacts crop yield in these regions [12].

Developing sustainable agriculture in arid and semi-arid regions presents several challenges due to their geographical location, limited irrigation water supply, low rainfall rates, and high temperatures, particularly during the spring and summer seasons. Agricultural soils in these regions are typically characterized by low water-holding capacities, high infiltration rates, high evaporation rates, and deep percolation, which can make the soil less fertile [13].

The sustainable use of scarce water resources is a priority for agricultural development in Iran. This is particularly important as constraints on water availability can lead to decreased water-use efficiency (WUE) and lower crop productivity. To increase the WUE of soils, a combination of strategies may be employed, such as alleviating water deficits, generating fewer plant residues, and applying natural and synthetic amendments [14].

To achieve sustainability in agriculture, it is crucial to develop and implement new methods that utilize water more efficiently and preserve soil moisture storage capacity while maintaining product quality and yield [15]. Additionally, including irrigation as part of the overall irrigation management strategy can lead to further improvements in water conservation [16].

Rainfed agriculture plays a significant role in the global food production of many countries. According to a report by the Food and Agriculture Organization (FAO), of the 1600 million hectares of cultivated land in the world, approximately 1300 million hectares (81 %) are rainfed. This land accounts for roughly 60 % of the world's crop production, highlighting the importance of rainfed agriculture in global food security [17,18].

There are several agricultural technology management methods and strategies that can improve productivity, reduce risks and vulnerabilities, and increase the stability and sustainability of rainfed agriculture through supplementary irrigation (SI) management [19]. In areas with limited water storage, an irrigation management strategy may involve the use of SI to augment soil moisture and enhance crop productivity [19]. Research has demonstrated that optimal agricultural crop growth can occur through the combination of SI, irrigation, and rainfall during sensitive phenological stages [20].

In recent years, carbonization technology has emerged as an efficient method for sequestering atmospheric carbon and reducing greenhouse gas emissions. Biomass carbonization can be achieved through various processes and is largely dependent on the amount and duration of heating. Slow pyrolysis is the most common method employed and has been extensively researched [21,22].

Biochar (BC) is a highly versatile, porous material that has garnered interest due to its substantial surface area, advantageous adsorption properties, low bulk density, and significant carbon content. Notably, BC has the potential to improve soil physicochemical properties, enhancing soil fertility, moisture retention, and agricultural productivity [23]. Moreover, BC has demonstrated its ability to reduce nutrient and fertilizer leaching in rainfed soils and increase soil nutrient and water retention, thanks to its inherent high specific surface area and surface charge density [24,25]. BC can possess varying qualities and characteristics based on the composition of plant residues used during its production, which can impact the levels of nitrogen, phosphorus, potassium (including soluble, exchangeable, and non-exchangeable potassium), and micronutrients (e.g., iron, manganese, copper, and zinc) [26].

Agricultural soils can experience numerous benefits when amended with BC, including enhancing water retention, increasing cation exchange capacity, and reducing leaching by adjusting soil pH and improving soil texture [27,28]. Importantly, the porous and chemical nature of BC makes it an eco-friendly soil amendment and it has a crucial role to play in sustainable agriculture by enhancing soil structure and properties [29].

BC application has shown promise in improving soil physicochemical properties and crop yield, as well as enhancing water and fertilizer efficiency, as evidenced by several studies [30–33]. For instance, Danso et al. (2019) demonstrated that the application of BC to soil (at a rate of 30 t ha^{-1}) increased maize yields and enhanced water productivity in semi-deciduous agroecological zones in eastern Ghana [30]. Li et al. (2018) reported that adding approximately 30 t ha^{-1} of BC to soil improves the soil's water-holding capacity, water and nutrient productivity, tomato yield, and cost-benefit tradeoffs under drip fertilization in a semi-arid region of Inner Mongolia, China [31]. Zhang et al. (2020) found that adding BC to soil, combined with daily drip fertigation in alkaline soils in the semi-arid area of Ningxia, China, overall improved soil physical quality, cucumber yield, and water fertilizer productivity [33]. Moreover, the combination of BC (at a rate of 20 t ha^{-1}) and inorganic fertilizer (at a rate of 300 kg ha^{-1}) in Akure, Nigeria, resulted in improved soil fertility, maize yield, and water efficiency under low rainfall conditions [34,35]. (BC has also been reported to improve the growth and yield of sunflowers and rapeseed under drought stress conditions [36,37].

As camelina emerges as an important industrial oil crop, there is a growing need for improved genetic resources and agronomic practices to enhance seed quality and production. Successful cultivation of camelina relies on the management of organic matter and soil moisture in rainfed conditions, as these can significantly affect crop yield. According to the Soil Survey Staff in the USA, high productivity, drought resistance, and water-use efficiency in the soil are key determinants of camelina yield, as they enable the crop to escape drought stress during the flowering and seed-filling stages. While camelina can be cultivated successfully with SI in semi-arid conditions, limited information is available on the impact of irrigation and soil moisture on the physio-biochemical properties and yield productivity of camelina at different growth stages [38].

In recent studies, the application of SI under different agro-climatic conditions has been shown to increase camelina seed yield, with higher water volumes leading to better outcomes [39]. This indicates that finding the suitable phenological stage for SI and increasing soil organic matter via BC can improve plant growth and increase the yield of rainfed crops, especially in dryland farming areas where water scarcity is a major issue. However, the cost-effectiveness of such interventions must be carefully evaluated, taking into account production costs associated with SI, BC application, and water usage.

The primary objective of this research is to investigate the impact of BC and SI treatments on the growth of camelina plants and their functional changes, with a focus on plant growth, seed and oil yield, yield components, oil content, and fatty acid profile. The study will explore how changes in these variables are influenced by different amounts of BC and SI applied at different phenological stages. The research findings are expected to yield valuable insights into optimal amounts of BC and SI applications and their scheduling to improve water-fertilizer use efficiency and enhance soil fertility, particularly in poorly fertile soils with low water capacity.

2. Materials and methods

2.1. Site characteristics

This research study was conducted in 2018–2019, at the Shahid Madani University of Azarbaijan in East Azarbaijan, Tabriz, Iran (35° 84′ N, 51° 81′ E and 1366 m above sea level) and investigated the effects of biochar (BC) and supplementary irrigation (SI) on the growth, yield, oil quantity and quality of Camelina plants under rainfed conditions. This region in Iran is characterized by a semi-arid climate with a mean annual precipitation of 298 mm and average monthly maximum and minimum temperatures of 27.4 and −1.2 °C, respectively. The site receives minimal rainfall and experiences high evaporation rates during the camelina growth season. Meteorological data on monthly mean air temperature and cumulative rainfall were collected from a nearby weather station throughout the experiment (Fig. 1). At the start of the study, soil samples were obtained from a 0–30 cm depth to analyze their properties. Table 1 displays the results of the soil and BC used in the experiment.

2.2. Experimental design

A field plot experiment was conducted using a split-plot arrangement with two variables: supplementary irrigation SI and BC. The SI treatments consisted of no irrigation (control), irrigation during the flowering stage (50 % blooming), and irrigation during the seed-filling stage. The BC treatments were subplots of BC0 (without BC, control), BC5 (5 t ha^{-1}), and BC10 (10 t ha^{-1}). The experiment consisted of 27 plots (9 treatments with 3 replicates each). The seedbed was prepared using a moldboard plow, disk, and furrow-maker, and experimental plots were established with dimensions of 2.5 × 2 m. The distance between adjacent replicates and main plots was 1 m, while the distance between subplots was 0.5 m. BC was mixed with the soil to a depth of 15 cm, 10 days prior to planting camelina seeds. The BC used was obtained from the Production Cooperative Company Fasle Panjom in Shiraz, Iran using pyrolysis at 500 °C, with its physical and chemical properties listed in Table 1. Camelina seeds were manually sown with a row spacing of 15 cm and plant spacing of 5 cm at a depth of 0.5–1 cm on November 17th, 2019.

Table 1
Properties of experimental soil (0–30 cm depth) at the start of the experiment and BC applied.

Item	BC	Item	Soil
Texture	NA	Sandy loam	
Organic matter (%)	13.89	Organic matter (%)	0.71
C/N	10.20	NA	
Organic carbon	8.09	NA	
Electric conductivity (EC) (ds/m)	0.2	Ec (dS/m)	1.36
pH	8.1	pH	8.2
N	0.79	N	0.07
Available P (mg kg^{-1})	0.14	P (mg kg^{-1})	7.8
Available K	0.17	K(mg kg^{-1})	162
Ca	4.26	NA	
mg	5.77	NA	
Cation-exchange capacity (CEC) (cmol$_c$ kg^{-1})	30.25	CEC (cmol$_c$ kg^{-1})	9.5
Bulk density (g cm^{-3})	1.40	Bulk density (g cm^{-3})	1.35
Ash content (%)	24.6	NA	

NA, not available.

2.3. Monitoring and harvest

Plant growth was monitored and assessed for potential pest and disease infestation by visiting the farm regularly throughout the experiment. No chemical interventions were used against pests or pathogens. Manual weeding was conducted multiple times. The plots were irrigated twice using the flood irrigation method, once during the flowering stage and once during the seed-filling stage.

2.4. Measurements and analysis

At full seed ripening, when at least 95 % of the siliques had turned brown and seed moisture was ≤12 % (BBCH 89), the above-ground biomass of Camelina plants was harvested manually. This involved sampling 10 rows from the central portion of each plot (~1 m2). The samples were then weighed, dried, and threshed for measurements of total biomass and seed yield. Additional measurements included plant height, lateral branch count, number of siliques, number of seeds per silique, and 1000-seed weight. Plant height was measured up to the tip of the apical meristem, while the number of branches, siliques, and seeds per silique were counted on the same plant used for height measurement. To assess seed yield, plants were manually threshed using small-seed-compatible sieves. Fresh weight was measured before drying in a

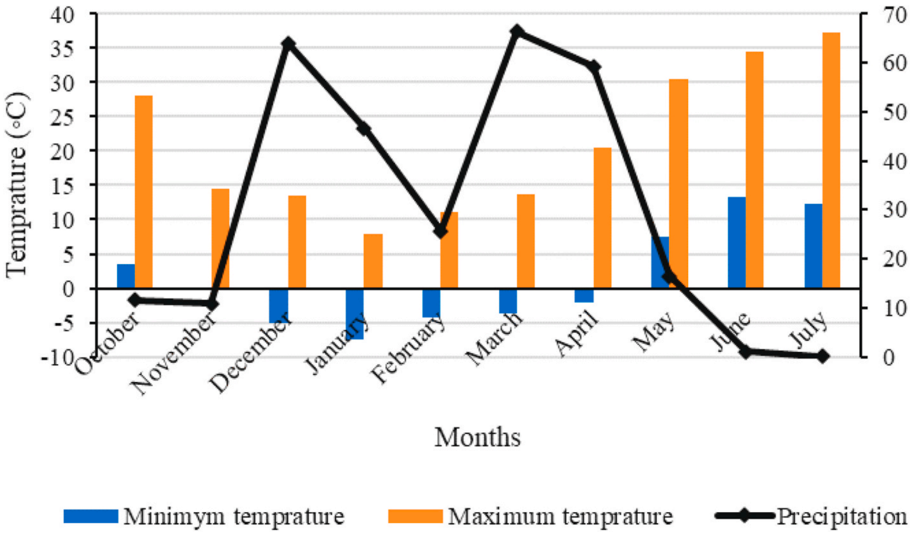

Fig. 1. Monthly precipitation, mean minimum and maximum air temperatures (°C) during the study period.

ventilated oven at 60 °C to obtain dry weight. The crop harvest index, which represented the efficiency of photosynthates translocation to harvestable products (seed), was calculated by dividing dry seed weight by dry weight of total above-ground crop biomass at harvest. The harvest index was expressed as a percentage, where HI = (EY/BY) x 1000. The 1000-seed weight was determined on representative seed samples from each plot using international seed testing guidelines.

2.5. *Oil content and yield*

Following harvest, the seeds were dried and powdered with an electrical grinder, and then extracted using a Soxhlet apparatus. Hexane was used as a solvent and evaporated in an evaporator, after which the oil content was determined. Oil yield was calculated by multiplying the seed yield and oil content. Specifically, the calculation was: Oil yield (kh ha^{-1}) = seed yield x oil content.

2.6. *Fatty acid profile*

To determine fatty acid composition, the Metcalf and Shmitz method (1966) was employed to convert the measurements into corresponding fatty acid methyl esters (FAME) [40]. A gas chromatography (Unicam 4600) equipped with a FID detector was used to identify the contents. The stationary phase was a capillary silica column BPX70 (30 m × 0.22 mm i.d, 0.25 μm film thickness (SGE)), and 0.2 μl of FAME sample was injected using a micro syringe. Helium was used as the carrier gas with a head pressure of 18 psi. The injector and detector temperatures were set to 250 °C and 300 °C, respectively. The oven temperature was ramped up from 160 °C to 200 °C at a rate of 2.0 °C/min and maintained at 200 °C for 40 min. The FAME samples were identified by comparing their retention time data and mass spectra with standards from Aldrich or Sigma. Fatty acid patterns were then calculated and evaluated based on the identified fatty acids.

2.7. *Statistical analysis*

Data were analyzed using Fisher's test for analysis of variance with fixed factors, which included BC (0 (control), 5 and 10 t ha^{-1}) and SI treatments (without irrigation and irrigation at the flowering and seed-filling stages) with Statistical Analysis Software (SAS, version 9.2). To check significant differences between the means Least significant difference (LSD) test and p values < 0.05 was used.

3. Results and discussion

3.1. *Plant height*

The height of the seedlings was significantly affected by the main effects and interaction effects of SI and BC (Table 2). The levels of BC did not differ substantially between the control and irrigation treatment during seeding. The study found that irrigation with BC5 during the flowering stage produced the tallest plants (63.20 cm) a significant increase of 18.99 % compared to the control plants (51.10 cm). Overall, the results illustrate a significant increase in Camelina plant height due to SI during the flowering stage, as shown in Fig. 2. Additionally, the interaction effect of BC and SI revealed that the treatments in which there was no BC and SI (control) caused a significant decrease in plant height, relative to the other treatments (Fig. 2) (see Fig. 3).

3.2. *Number of lateral branches*

The number of lateral branches in plants was significantly impacted by the main effects of BC and SI, while the interaction effects showed no significant effect (Table 2). Analysis of mean values associated with the main effects revealed that irrigation during the flowering stage significantly increased the number of lateral branches, in comparison to the rainfed condition and SI during the seed-filling stage. As such, the application of SI during the flowering stage resulted in the highest number of lateral branches. Specifically, the maximum number of lateral branches observed was 8.55 during the flowering stage, which was 19.65 % and 18.95 % higher than that of the control treatment and irrigation during the seed-filling stage, respectively (Table 3). Moreover, the main effects of BC application (at both levels of BC5 and BC10) demonstrated a significant increase relative to the control group. In particular, the highest number of lateral branches was achieved in response to BC10 application, which represented an increase of 26.91 % and 13.80 % compared to the values observed in the BC0 and BC5 treatment groups, respectively (Table 3).

3.3. *Number of siliques per plant*

According to the analysis the number of siliques in plants was significantly influenced by the main and interaction effects of SI and BC (Table 2). A comparison of means revealed no noteworthy difference in the impact of various BC levels when compared to rainfed irrigation and SI application during the seed-filling and flowering stages. However, BC displayed a significant impact on flowering under rainfed conditions. Consequently, the highest number of siliques (241.32 plant^{-1}) was observed under the treatment of SI during the flowering stage with the application of BC10, resulting in a 52.96 % increase relative to the control (113.13 plant^{-1}) (Fig. 4) (see Fig. 5).

3.4. *Silique weight*

The analysis demonstrated that the weight of silique significantly impacted by both SI and BC (Table 2). Additionally, mean comparisons indicated noteworthy differences in weight between the control and BC5, as well as between the control and BC10 across all SI levels. The highest weight of silique (1.50 g plant^{-1}) was achieved in response to SI during the flowering stage along with the application of BC10, which is comparable to the control treatment (without SI and BC0) (0.62 g plant^{-1})), thereby presenting a 58.67 % increase. When comparing the control treatment (without BC and SI) with other treatments (Fig. 4), it was observed that this treatment led to a significant reduction in camelina silique weight.

Table 2
Analysis of variance (mean of squares) of the growth and morphological traits of camelina under the effect of supplementary irrigation and biochar in the studied traits.

S·O·V	df	Plant height	Number of lateral branches plant^{-1}	Number of silique plant^{-1}	Silique weight	Number of Seeds Silique^{-1}
Block	2	6.56	3.35	999.27	0.0073	0.56
Supplementary irrigation)SI(	2	150.31**	8.19**	5518.24**	0.4075**	4.57**
Main error	4	18.64	1.02	607.09	0.0433	1.36
Biochar)BC(	2	19.02*	12.11**	5099.54**	0.5326**	1.86*
SI × BC	4	11.28*	0.57 ^{ns}	2518.05**	0.0447*	0.08 ^{ns}
Error	12	3.42	1.09	463.13	0.0134	0.31
C·V (%)	–	9.84	3.50	5.51	11.99	4.50

ns ** and *: non-significant, and significant in 1 % and 5 % level, respectively.

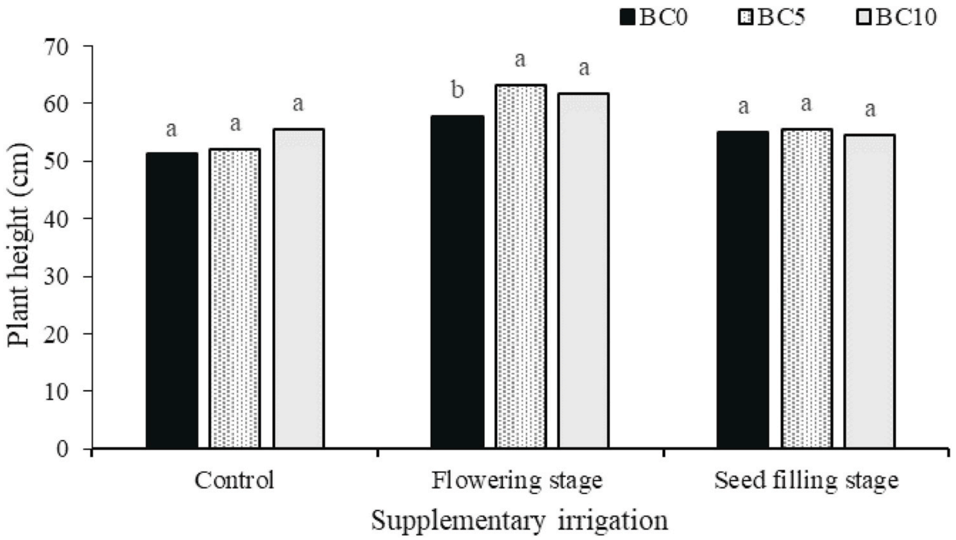

Fig. 2. Effect of supplementary irrigation and BC interaction on camelina height. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

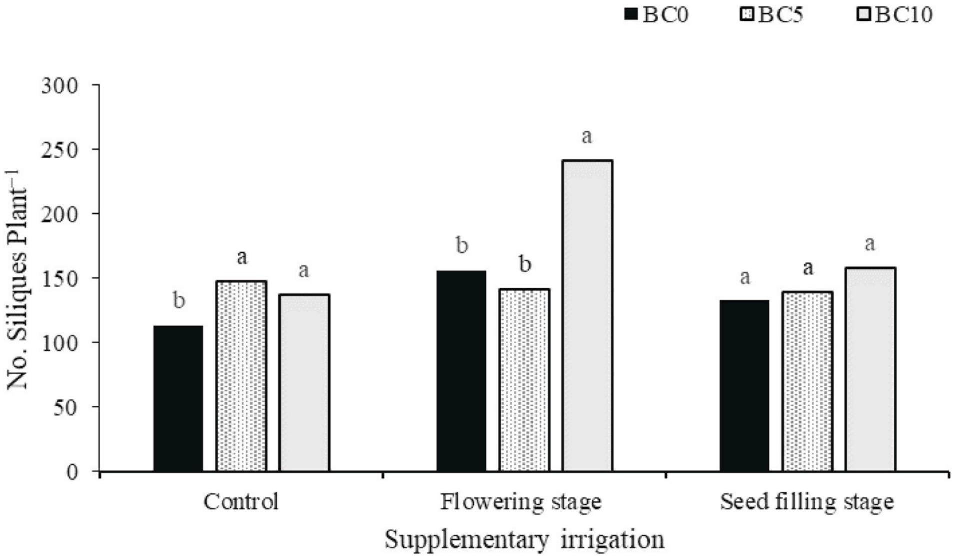

Fig. 3. Effect of supplementary irrigation and BC interaction on number of siliques. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

Table 3

Mean comparisons of the Supplementary irrigation on morphological and yield traits of camelina.

Supplementary irrigation	Plant height (cm)	Number of lateral branches plant −1	Number of silique plant-1	Silique weight (g)	Number of Seeds Silique-1	1000-Seed Weight (g)	Above-Ground Biomass (kg ha-1)	Oil yield (kg ha-1)	Oil content (%)	Harvest index (%)	Seed yield (kg ha-1)
Rainfed condition	52.98^b	6.87^b	132.49^b	0.82^b	13.04^a	0.98^b	5289.6^b	477.82^b	32.31^b	28.01^a	1473.4^b
SI at flowering stage	60.87^a	8.55^a	179.82^a	1.25^a	13.41^a	1.07^a	7183.5^a	777.38^a	36.14^a	30.65^a	2153.1^a
SI at seed filling stage	55.09^b	6.93^b	143.52^b	1.03^{ab}	12.04^a	1.08^a	6676.9^a	734.7^a	35.30^a	31.08^a	2077.7^a

Means that have a common letter have not significantly different together ($p < 0.05$). Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

3.5. Number of seeds in silique

Based on the analysis, irrigation and BC had significant main effects on the number of seeds per silique, while the interaction effects of SI and BC did not show a significant effect on seed count (Table 2). Mean value comparisons of the main effects of irrigation did not reveal a significant

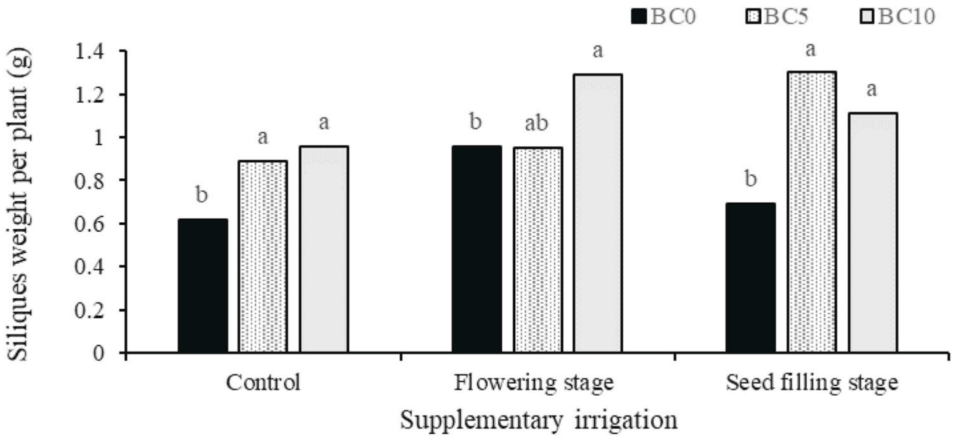

Fig. 4. Effect of supplementary irrigation and BC interaction on camelina siliques weight. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

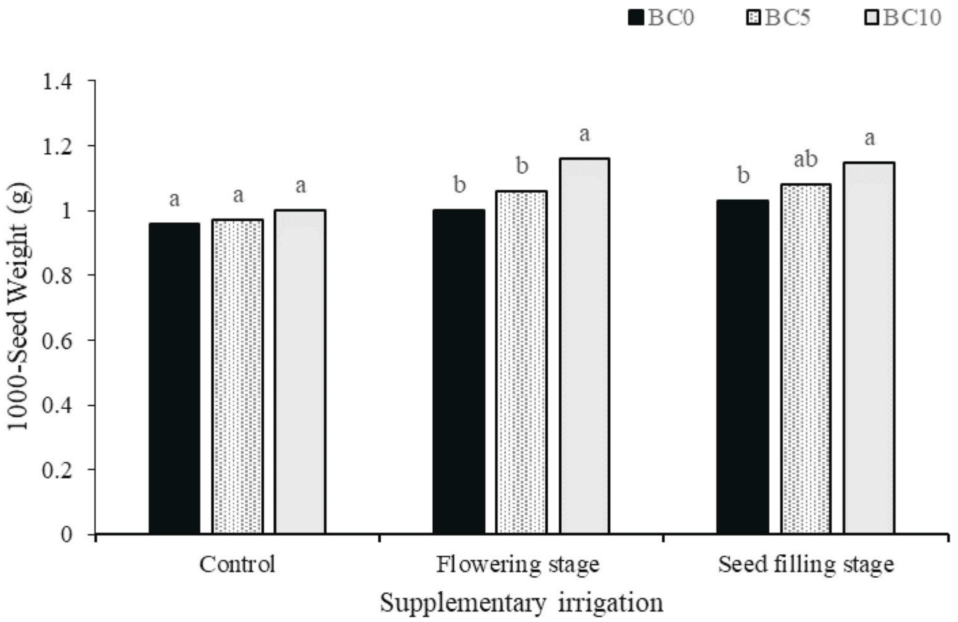

Fig. 5. Effect of supplementary irrigation and BC interaction on camelina1000-seed weight. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

difference in seed count across various SI levels and rainfed conditions ($P \leq 0.05$), as shown in Table 3. The application of BC10 resulted in the highest number of seeds per silique (13.34), followed by BC5 (12.67) and BC0 (12.48), respectively (Table 3). Significant increases in seed count were observed with the application of BC10.

3.6. *1000-Seed weight*

The analysis results on the 1000-seed weight indicated significant effects of SI and BC (Table 4). Mean comparisons demonstrated that different BC levels had no significant impact on the control treatment (no SI). However, the application of BC during both stages of SI led to an increase in 1000-seed weight. The highest 1000-seed weight (1.16 g)

Table 4
Analysis of variance (mean of squares) of the yield traits of camelina under the effect of supplementary irrigation and biochar in the studied traits.

S·O·V	df	1000-Seed Weight	Above-Ground Biomass	Seed yield	Harvest index	Oil content	Oil yield
Block	2	0.002	992998.16	608555.74	85.51	1.13	72297.30
Supplementary irrigation (SI)	2	0.032**	8652157.92**	1249214.86**	24.77^{ns}	36.51**	23609.81**
Main error	4	0.004	987033.41	74372.75	10.89	0.733	9292.42
Biochar (BC)	2	0.025**	7180215.37**	502146.02*	12.00^{ns}	6.198**	83258.10**
SI × BC	4	0.003*	2816471.40*	315105.27*	5.68^{ns}	1.99*	36049.19*
Error	12	0.0007	852939.29	78292.01	24.37	0.607	10893.92
C·V (%)	–	14.46	4.09	5.73	0.91	11.59	6.33

ns ** and *: non-significant, and significant in 1 % and 5 % level, respectively.

occurred due to BC10 and irrigation at flowering, showed an increase of 17.24 % compared to the control (0.96 g). The findings revealed that SI at both stages, flowering and seed-filling, significantly influenced the 1000-seed weight.

3.7. Above-ground biomass

Table 4 revealed that both SI and BC had significant effects, along with an interaction effect on above-ground biomass. Mean comparison analysis indicated no significant differences in the effects of various BC levels between the no irrigation control treatment and irrigation during the seed-filling stage. The highest total biomass (9250 kg ha^{-1}) was achieved at the flowering stage using BC10, representing a 53.19 % surge in comparison to the control (4329.5 kg ha^{-1}) without SI and BC (Fig. 6). The correlation analysis showed a positive relationship between biomass and several factors such as the number of siliques, seed yield per hectare, silique weight, lateral branches, plant height, and 1000-seed weight. As each of these factors increased, total biomass also increased (see Fig. 7).

3.8. Seed yield

Table 4 indicated that both SI and BC had significant main and interaction effects on camelina seed yield. Mean value comparisons revealed that different levels of BC did not significantly differ in their effects on seed yield between rainfed and irrigation conditions during the seed-filling stage, although BC application did improve yield. The interaction between BC0 and SI showed that BC0 in the rainfed condition resulted in the lowest seed yield. In contrast, irrigation during the flowering stage with BC10 resulted in the highest seed yield (2751.8 kg ha^{-1}) compared to the control (1232.3 kg ha^{-1}), indicating a significant 55.22 % increase in yield.

3.9. Harvest index

Table 4 from the analysis indicated that there was no significant interaction between SI and BC in relation to the harvest index. The treatment with BC5 and irrigation during flowering resulted in the highest harvest index, although the difference was not statistically significant. Furthermore, the analysis of trait correlations revealed that seed yield had the strongest correlation with the harvest index.

3.10. Oil yield and content

Table 4 revealed that the interaction effect of SI and BC had a significant impact on oil content and yield. However, there were no significant differences observed in the mean oil content and yield between the various levels of BC under SI during flowering and seed filling stages. The application of BC in the rainfed condition led to a greater increase in oil content and yield. The use of BC5 resulted in the highest oil content when irrigation was applied during the flowering stage, demonstrating a 15.12 % increase compared to the control (rainfed condition and BC0) (Fig. 8). On the other hand, the highest oil yield was achieved when irrigation was applied at the flowering stage with BC10, presenting a 61.44 % increase compared to the control treatment (rainfed condition and BC0) (Fig. 9).

3.11. Fatty acids compositions

Table 5 presented the results of gas chromatography (GC) analysis of camelina oil, identifying 14 types of fatty acids. The fatty acid profile was consistent with previous studies [41–43], and all fatty acid constituents were affected by SI and BC interactions. Oleic, linoleic, linolenic, eicosadienoic, and palmitic acid were the main fatty acids in camelina seed oil, and all were influenced by the treatments. Saturated fatty acids (SFAs) such as myristic acid, palmitic acid, stearic acid, and behenic acid were also present in the oil. The application of BC10 and SI led to the most significant decrease in stearic and palmitic acids, respectively, when compared to the control (Table 5).

Table 5 showed that the highest percentage of unsaturated fatty acids (UFAs) in camelina seed oil (92.97 %) resulted from the application of BC10 and SI at the seed-filling stage. Conversely, the lowest percentage of UFAs (86.21 %) was obtained from the application of BC0 and rainfed conditions. The control treatment (no SI and BC0) yielded the highest percentage of saturated fatty acids (SFAs) at 12.10 %. The amount of UFAs in camelina seed oil was influenced by BC and soil water availability. Palmitoleic, oleic, linoleic, linolenic, eicosanoic, eicosatrienoic, arachidonic, erucic, and docosapentaenoic acids were the UFAs identified in camelina seed oil. The highest amounts of oleic and linolenic acids were observed in response to BC10 along with SI during the seed-filling stage, increasing them by 10.2 % and 11.3 %, respectively. The highest level of linoleic acid was obtained from the application of BC0 and SI at the seed-filling stage, increasing it by 4.9 % compared to the

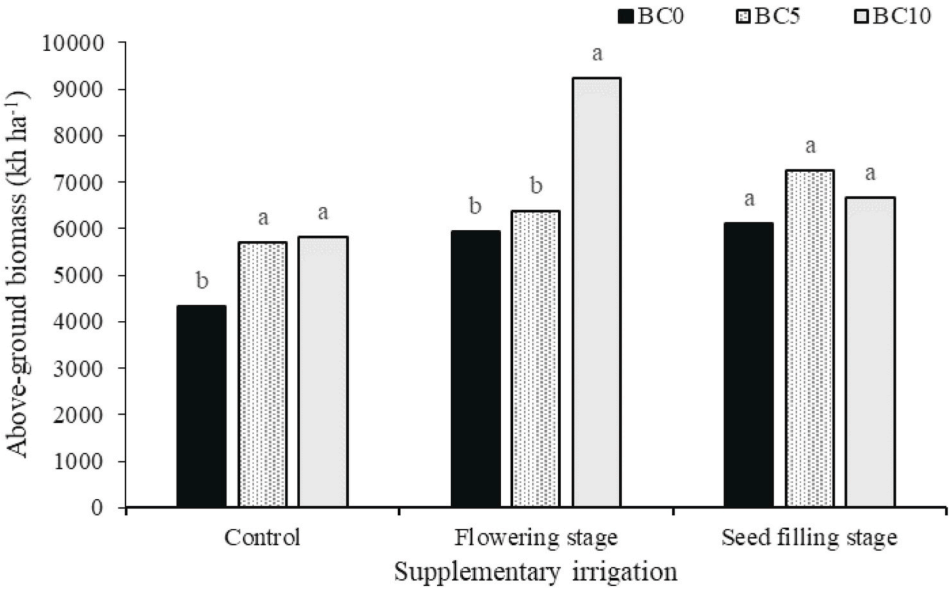

Fig. 6. Effect of supplementary irrigation and BC interaction on camelina biomass weight. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

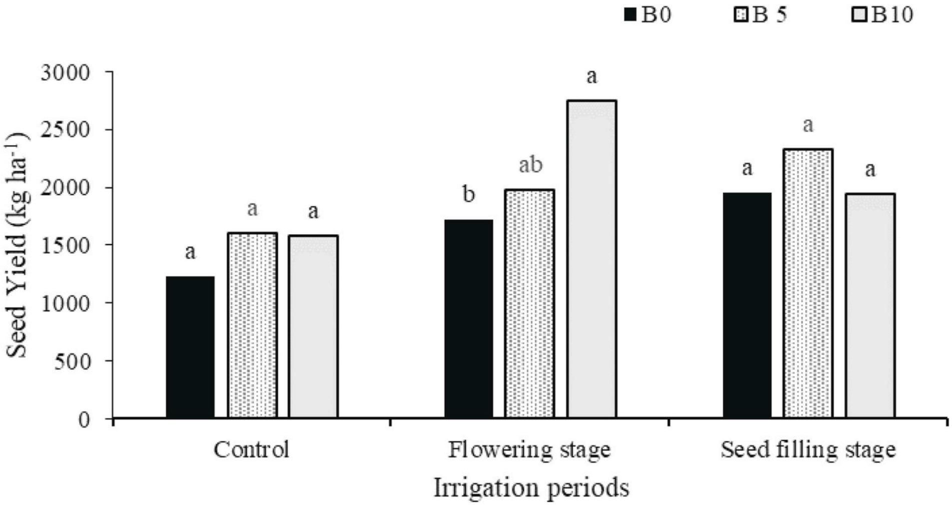

Fig. 7. Effect of supplementary irrigation and BC interaction on camelina seed yield. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

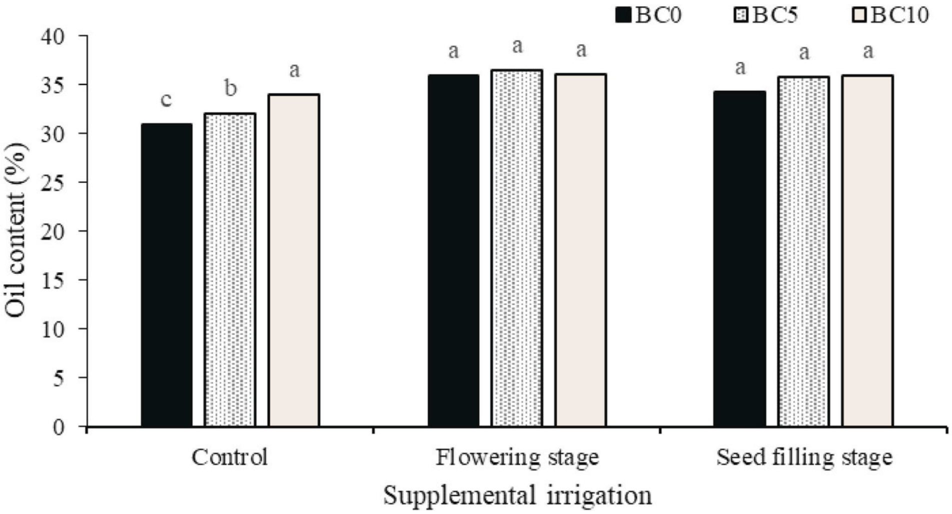

Fig. 8. Effect of supplementary irrigation and BC interaction on camelina oil content. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

control. Moreover, a high seed oil content was associated with a decrease in SFAs when SI and BC were applied.

4. Discussion

The combination of biochar (BC) and supplemental irrigation (SI) has presented a promising strategy for reducing the use of chemical inputs and mitigating drought stress in rainfed conditions. According to the findings of the present study and previous research, BC can alleviate the negative effects of drought stress and enhance plant growth by providing benefits such as increased cation exchange power, improved nutrient and moisture availability, and an ideal habitat for soil microorganisms [44,45]. In addition, BC's large pores and high specific surface area can act as physical support for soil microorganisms, facilitating root penetration and elongation, which ultimately leads to increases in plant height and development [45]. Moreover, the study found that BC, particularly at a rate of 5 t ha^{-1}, can promote plant height and development in rainfed conditions. SI during the flowering stage significantly increased Camelina plant height, while irrigating during seed filling led to competition and moisture limitations, ultimately leading to reduced plant height. According to research of Hussain et al. (2008), reducing water availability during the flowering stage could result in shorter plants due to dehydration, reduced turgidity, and altered protoplasmic activity, leading to a decline in cell division and lifespan [46]. The study also found that a higher dose of BC (B10) significantly increased plant height compared to the control, corroborating earlier research indicating its favorable impact on crop growth. The increased nutrient absorption, soil microbial activity, and photosynthetic rate observed after BC application contributed to greater overall plant growth. As a notable indicator of plant morphological growth, the number of lateral branches is influenced by environmental factors such as humidity and soil characteristics, which affect water availability and nutrient absorption during the flowering stage. Similarly, including BC in poor soils can enhance macro- and micronutrient availability and promote better photosynthesis and more branches in plants [47,48].

Drought stress during the reproductive stage of camelina plants can impact the number of siliques per plant and the number of seeds per silique prior to pollination. This study reveals that the application of BC and SI significantly increases the number of siliques per plant. Low soil moisture can reduce the potential for silique and seed production in plants that bloom during the flowering stage, impacting the plant's yield components [49,50]. The application of BC improves soil properties,

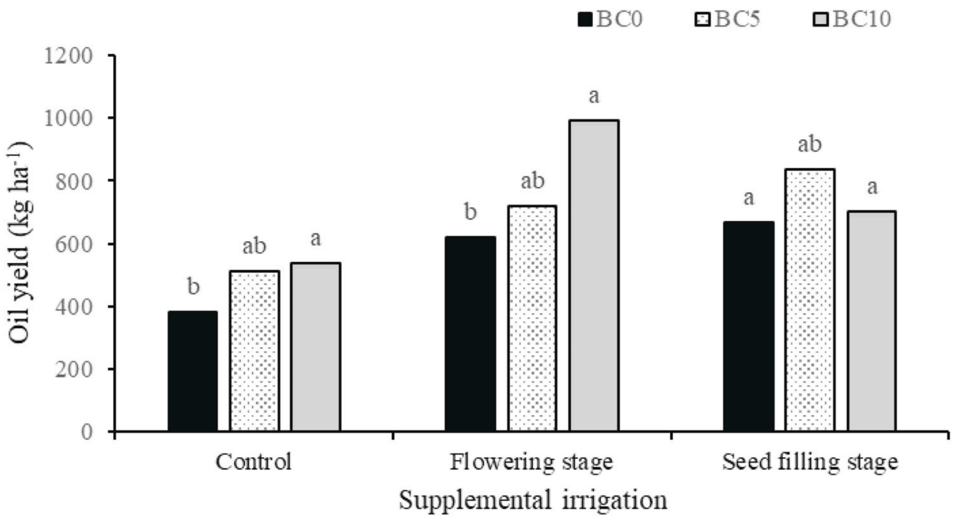

Fig. 9. Effect of supplementary irrigation and BC interaction on camelina oil yield. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the LSD test.

Table 5
Fatty acids composition of camelina under supplementary irrigation and BC interaction.

Fatty acids	Control	BC_0^+ SI in the flowering stage	BC_0^+ SI in the seed filling stage	BC_5+rainfed condition	BC_{10}+rainfed condition	BC_5+ SI in the flowering stage	BC_{10}+ SI in the flowering stage	BC_5^+ SI in the seed filling stage	BC_{10}^+ SI in the seed filling stage
Myristic acid	0.70	0.09	0.08	0.71	0.09	0.10	0.10	0.12	0.11
palmitic acid	7.97	6.35	6.08	7.80	6.25	6.15	6.02	5.17	4.91
Palmitoleic acid	0.37	0.20	0.19	0.35	0.16	0.18	0.19	0.19	0.22
Stearic acid	3.06	2.60	2.40	2.80	2.47	2.46	2.49	2.45	1.71
Oleic acid	18.29	19.25	18.57	18.64	19.01	19.26	19.69	20.30	20.37
Linoleic acid	21.13	22.22	19.50	20.45	21.32	20.63	20.87	19.91	20.91
Linolenic acid	27.52	28.33	30.26	28.20	29.51	28.48	30.06	30.81	31.03
Eicosenoic acid	1.85	1.67	1.85	1.91	1.70	1.67	1.66	1.59	1.65
Eicosadienoic acid	10.59	13.36	14.73	10.48	13.33	13.40	13.37	13.55	13.88
Eicosatrienoate acid	1.83	1.66	1.88	1.78	1.66	1.62	1.69	1.59	1.52
Arachidonic acid	0.90	0.81	0.95	0.90	0.86	0.80	0.15	0.90	0.41
Behenic acid	0.38	0.32	0.31	0.39	0.35	0.79	0.27	0.30	0.30
Erucic acid	3.35	2.89	2.83	3.37	3.04	4.18	3.08	2.80	2.79
Docosapentaenate	0.37	0.28	0.36	0.98	0.26	0.28	0.34	0.32	0.20
Total	98.31	100	100	98.77	100	100	100	100	99.99
Unsaturated fatty acids (UFAs)	86.21	90.64	91.13	87.06	90.85	90.51	91.12	91.96	92.97
Saturated fatty acids (ΣSFAs)	12.10	9.36	8.87	11.71	9.15	9.49	8.88	8.04	7.02

enhances nutrient availability, and could lead to an increase in vegetative growth rates, linear growth rates, and dry matter accumulation, which promotes greater silique production [36,51]. According to Oguz et al. (2022), drought stress during the flowering stage reduces leaf water content, chlorophyll, and photosynthesis rates, leading to lower plant yields [52]. Using specific compounds that improve soil moisture retention can enhance crop water-use efficiency and mitigate drought stress severity under rainfed conditions, particularly during critical plant growth stages. Organic materials like BC have shown remarkable soil conditioning and self-moisture retention properties [53].

The previous research by Akhtar et al. (2014) investigated the influence of BC on tomato physiology, yield, and quality under varying irrigation regimes [54]. The study found that BC improved plant physiology, yield, relative leaf moisture, water use efficiency, fruit quantity, and quality while preserving soil moisture. This outcome is consistent with the current research on camelina, where BC application increased sub-branch and silique weight under rainfed conditions. Furthermore, BC application increased seeds per silique, which is a crucial component in determining a plant's ability to generate and acquire photosynthetic assimilates [55]. The application of BC optimizes nutrient absorption by enhancing soil properties and providing nutrients. Research shows that soil amendment with BC increases soybean seeds per pod due to elevated nutrient absorption [51]. Drought stress can significantly affect plant growth and seed production, particularly during reproduction. The lack of moisture can reduce the production of flower stems, limit pollination, impede growth of pollen grains and tubes, and lead to wilting of stigma, ultimately affecting the number of seeds produced [56]. Photosynthetic assimilates flow after pollination, and their quantity has a direct impact on the 1000-seed weight. The lack of moisture in rainfed conditions hinders nutrient absorption, reducing photosynthesis, and subsequently, the 1000-seed weight and the food reserves in seeds [57]. An increase in photosynthetic activity is closely linked to achieving a high 1000-seed weight. The storage of photosynthetic materials in the seeds contributes to heavier seeds, which reflects in the 1000-seed weight. Nevertheless, environmental factors play a crucial role in the seed filling process; for instance, water deficit conditions during flowering and reproduction shorten the seed filling period, reducing the assimilates accumulation period, leading to a lower 1000-seed weight [31]. In this study, the application of BC10 increased the 1000-seed weight significantly compared to BC5 and the absence of BC. BC improved soil fertility by increasing nutrient availability, stabilizing soil moisture, and enhancing nitrogen retention, consequently producing heavier seeds.

The current study found that a combination of BC and SI significantly improved total biomass yield and seed yield in camelina plants. Previous research by Neupane et al. (2020) found that water availability significantly impacts camelina crown cover and yield components, and there is a strong correlation between grain yield and water use [58]. The combination of BC and SI improved water availability, reduced drought stress, stimulated vegetative and reproductive growth, and increased total biomass yield in camelina plants in this study. Seed yield is a crucial variable in crop production, and water supply during the flowering stage is vital for seed filling and higher yield in camelina plants [59]. Previous research by Aiken et al. (2015) demonstrated that oilseed crops, including camelina, grown under dryland conditions were limited by poor soil moisture availability and heat stress during the flowering and seed formation stages [60]. Inadequate irrigation can lead to premature crops with poor seed yield due to the effects of drought stress, while irrigation treatments can result in improved plant growth and a higher economic yield. Similarly, Ahmed et al. (2020) found that different irrigation regimes significantly impacted camelina yield and yield-contributing traits, with a decrease in soil water availability limiting the development of yield-related traits and reducing seed yield [59]. The lack of irrigation during the flowering stage led to a reduction in yield due to fewer siliques, flowers, silique abortion, and shorter seed filling periods. The application of BC in this study promoted an increase in seed formation, more siliques per plant, more seeds per silique, and a greater 1000-seed weight, resulting from enhanced soil properties and nutrient uptake. Similarly, Agarwal et al. (2021) found that irrigation during the flowering stage was the most effective way to improve seed yield in camelina [61]. Drought stress resulting from a lack of soil moisture during the reproductive stage can lead to adverse consequences, such as leaf senescence and a reduction in photosynthetic rate, thereby limiting seed yield [62,63].

The study investigated the impact of inadequate irrigation and the use of BC on rapeseed cultivars' yield and yield-related components. The study findings suggest that flower and panicle formation are the most sensitive growth phases affected by drought stress. Angadi et al. (2003) showed that withholding irrigation during the flowering period results in the greatest decrease in rapeseed seed yield [64]. Proper water supply, together with BC utilization, contributes to nutrient retention, stimulates vegetative and reproductive growth, improves photosynthetic assimilates' production, and aids their transfer to seeds. These treatments increase seed yield by alleviating the occurrence of leaf senescence under rainfed conditions. Huang et al. (2019) demonstrated that BC application helps ensure optimal soil acidity for nutrient absorption and sustainability [65]. A decrease in water supply affects seed yield and yield-related components in camelina negatively. Past studies [58,66,67] suggest a strong correlation between water consumption and seed yield in camelina, with the former positively affecting crown cover and yield component development. The harvest index is crucial in determining seed yield and is inversely associated with biological yield. Neupane et al. (2020) found that different camelina cultivars, irrigation regimes, year and their interaction did not significantly influence harvest index [58]. Nonetheless, Li et al. (2018) suggest that a decrease in harvest index under water-deficit conditions is likely due to low leaf count [68].

Drought stress leads to a reduction in canola plant size and leaf surface, resulting in a decrease in straw and stubble yield and rapeseed yield, as well as leaf aging acceleration. Li et al. (2018) found that cultivars with a high harvest index and more photosynthetic materials allocated to seeds adapt better to drought stress, improving their drought resistance [68]. The increase in harvest index may result from increasing the supply of carbohydrates required for triacylglycerol synthesis and subsequent accumulated seed oil during flowering and seed development. Environmental conditions, including nutrition, temperature, and water availability, influence the content of seed oil in crops [69]. Drought stress significantly reduces soybean oil production by decreasing photosynthesis and shortening the seed filling period, rendering lipid accumulation highly susceptible to stress [70]. Moderate BC application has been found to favor optimal plant growth, improve soil pH, and nutrient balance, leading to optimal growth. Dispenza et al. (2016) note that a balanced amount of BC treatment is favorable for plant growth [71]. Jemal et al. (2016) observed that combining BC5 and SI during the flowering stage resulted in the highest seed oil content [72]. BC has a positive effect on soybean oil quality [73]. Rainfall and irrigation also impact crop yield and oil content.

Water deficits during the reproductive stage can significantly impact plant performance, leading to decreased oil content and linolenic acid content in seeds [64]. However, the application of BC and SI has been found to increase plant drought tolerance and crop yields, making it a crucial consideration for Iranian rainfed crops [74]. The current study demonstrates a correlation between the percentage of linolenic acid and seed oil content, highlighting the importance of efficient water utilization in rainfed conditions. Results from the current study and Pavlista et al. (2016) indicate that the application of BC and SI during the seed-filling stage can increase linolenic acid content in oilseeds [75]. The fatty acid composition of camelina oil is primarily composed of linolenic acid, followed by linoleic acid and oleic acid [76]. BC and irrigation can impact the fatty acid profile in oilseed crops, particularly during flowering and seed-filling stages, where they can interfere with enzymes involved with the metabolism of polyunsaturated fatty acids (PUFAs), leading to an increase in their content [77]. The study by Moradi et al. (2023) demonstrated that applying BC to rapeseed cultivars improved seed yield quality through an increase in monounsaturated fatty acids (MUFAs) and a decrease in PUFAs [78].

The application of SI during the flowering and seed-filling stages can increase the ratio of dietary PUFA to saturated fatty acid (SFA), which helps prevent cardiovascular diseases [74]. Irrigation has also been found to increase the proportion of linolenic acid in camelina oil while decreasing the levels of linoleic acid [75]. The highest quantities of linolenic acid were generated in camelina during the flowering and seed-filling stages when rainfall was above average [42]. An inverse relationship between saturated and MUFAs in oilseeds, such as camelina, has been observed (Table 5). The application of appropriate amounts of BC and SI during seed development can increase PUFAs in camelina seeds, leading to higher levels of linoleic acid, SFAs, and MUFAs in the seeds. The combined application of BC and SI has been found to be the most effective way of improving the unsaturated fatty acid (UFA) ratio. Camelina seed oil contains significant amounts of eicosadienoic acid (10.48–14.73 %), which can be a valuable source of medium-chain fatty acids in the bio-based industry. The application of appropriate amounts of BC can increase UFAs by boosting plant photosynthesis through the increased assimilation of carbon. SFAs have lower fluidity than unsaturated fatty acids, making them less influenced by irrigation and BC. On the other hand, UFAs are critical for the structure and function of organisms and contain several essential fatty acids that cannot be synthesized by the human body. The balanced amount of essential fatty acids in the diet is vital because humans and mammals cannot synthesize them. Besides the agricultural benefits, camelina has a unique oil composition suitable for various industrial applications such as cosmetics, nutraceuticals, green polymers, and biofuels.

5. Conclusion

The application of BC improved the growth, yield, and water-related parameters of Camelina, both under control and SI conditions. When used in rainfed conditions, BC serves as a water- and energy-saving approach. It is an organic fertilizer that, when combined with SI and applied to Camelina, assists plants in accessing more water and nutrients, thus leading to increased plant growth, photosynthesis, seed yield, and oil quality. This study discovered that the flowering stage is most sensitive to drought stress, and the best treatment for alleviating this stress on Camelina is the application of BC in the soil. The application of SI at the flowering stage in combination with BC10 was also shown to increase seed yield, oil yield, and oil quality, resulting in increased water absorption efficiency in conditions of insufficient rainfall. This combination of treatments not only assists in reducing the use of chemical inputs and preserving the environment under rainfed conditions but also promotes the sustainable production of Camelina by revitalizing poor soils. It is a suggested promising approach towards drought stress alleviation while restoring agro-ecosystems and promoting land resource sustainability, which has far-reaching benefits for food security.

CRediT authorship contribution statement

Saeid Hazrati: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Naser Rostami:** Investigation, Data curation, Methodology, Project administration, Writing – original draft. **Hamid Mohammadi:** Formal analysis, Methodology, Writing – review & editing. **Mohammad-Taghi Ebadi:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

There is no conflict of interest.

Data availability

Data will be made available on request.

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References

[1] E.J. Murphy, Camelina (*Camelina sativa*), in: Industrial Oil Crops, AOCS press, 2016, pp. 207–230.
[2] J. Zubr, Oil-seed crop: *Camelina sativa*, Ind. Crops Prod. 6 (1997) 113–119.
[3] H. Belayneh, R. Wehling, E. Cahoon, N. Ciftci, Extraction of omega-3-rich oil from *Camelina sativa* seed using supercritical carbon dioxide, J. Supercrit. Fluids 104 (2015) 153–159.
[4] T. Mandáková, M. Pouch, J.R. Brock, I.A. Al-Shehbaz, M.A. Lysak, Origin and evolution of diploid and allopolyploid camelina genomes were accompanied by chromosome shattering, Plant Cell 31 (2019) 2596–2612.
[5] V. Razmaitė, V. Pileckas, S. Bliznikas, A. Šiukščius, Fatty acid composition of *Cannabis sativa, Linum usitatissimum* and *Camelina sativa* seeds harvested in Lithuania for food use, Foods 10 (2021) 1902.
[6] M. Berti, B. Johnson, D. Ripplinger, R. Gesch, A. Aponte, Environmental impact assessment of double-and relay-cropping with winter camelina in the northern Great Plains, USA, Agric. Syst. 156 (2017) 1–12.
[7] S. Chaturvedi, A. Bhattacharya, S.K. Khare, G. Kaushik, *Camelina sativa*: an emerging biofuel crop, Handbook of Environmental Materials Management (2018) 1–38.
[8] M. Von Cossel, I. Lewandowski, B. Elbersen, I. Staritsky, M. Van Eupen, Y. Iqbal, E. Alexopoulou, Marginal agricultural land low-input systems for biomass production, Energies 12 (2019) 16, 3123.
[9] A.K. Obour, H.Y. Sintim, E. Obeng, J. Zheljazkov, Oilseed camelina (*Camelina sativa* L Crantz): production systems, prospects and challenges in the USA great plains, Adv Plant Agric Res 2 (2015) 1–10.
[10] A. Royo-Esnal, F. Valencia-Gredilla, Camelina as a rotation crop for weed control in organic farming in a semiarid mediterranean climate, Agriculture 8 (2018) 156.
[11] M. Faisal, M.A. Iqbal, S.K. Aydemir, A. Hamid, N. Rahim, A. El Sabagh, A. Khaliq, M.H. Siddiqui, Exogenously foliage applied micronutrients efficacious impact on achene yield of sunflower under temperate conditions, Pak. J. Bot 52 (2020) 1215–1221.
[12] M. Faramarzi, H. Yang, R. Schulin, K.C. Abbaspour, Modeling wheat yield and crop water productivity in Iran: implications of agricultural water management for wheat production, Agric. Water Manag. 97 (2010) 1861–1875.
[13] A. Aldababseh, M. Temimi, P. Maghelal, O. Branch, V. Wulfmeyer, Multi-criteria evaluation of irrigated agriculture suitability to achieve food security in an arid environment, Sustainability 10 (2018) 803.
[14] B. Nazari, A. Liaghat, M.R. Akbari, M. Keshavarz, Irrigation water management in Iran: implications for water use efficiency improvement, Agric. Water Manag. 208 (2018) 7–18.
[15] S.H. Muhie, Novel approaches and practices to sustainable agriculture, J Agric Food Res 100446 (2022).
[16] J. Berbel, C. Gutiérrez-Martín, A. Expósito, Impacts of irrigation efficiency improvement on water use, water consumption and response to water price at field level, Agric. Water Manag. 203 (2018) 423–429.
[17] FAO, The Future of Food and Agriculture – Trends and Challenges, 2017. Rome.
[18] FAO, The state of the world's land and water resources for food and agriculture – systems at breaking point, Synthesis report (2021), https://doi.org/10.4060/cb7654en. Rome.
[19] T. Oweis, A. Hachum, Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa, Agric. Water Manag. 80 (2006) 57–73.
[20] T. Oweis, A. Hachum, J. Kijne, Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in Dry Areas, vol. 7, IWMI, 1999.
[21] S. Brick, S. Lyutse, Biochar: Assessing the Promise and Risks to Guide US Policy, Natural Resources Defense Council, USA, 2010.
[22] J. Manyà, Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs, Environ. Sci. Technol. 46 (2012) 7939–7954.
[23] R. Kookana, A.K. Sarmah, L. Van Zwieten, E. Krull, B. Singh, Biochar application to soil: agronomic and environmental benefits and unintended consequences, Adv. Agron. 112 (2011) 103–143.
[24] D. Laird, P. Fleming, B. Wang, R. Horton, D. Karlen, Biochar impact on nutrient leaching from a Midwestern agricultural soil, Geoderma 158 (2010) 436–442.
[25] T. Abbas, M. Rizwan, Sh Ali, M. Zia-Ur-Rehman, M.F. Qayyum, F. Abbas, F. Hannan, J. Rinklebe, Y. Sik Ok, Effect of biochar on cadmium bioavailability and uptake in wheat (*Triticum aestivum* L.) grown in a soil with aged contamination, Ecotoxicol. Environ. Saf. 140 (2017) 37–47.
[26] J. Tang, W. Zhu, R. Kookana, A. Katayama, Characteristics of biochar and its application in remediation of contaminated soil, J. Biosci. Bioeng. 116 (2013) 653–659.
[27] B. Glaser, Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century, Philosophical Transactions of the Royal Society. Biol Sci 362 (2007) 187–196.
[28] H. Wan, Y. Chen, B. Cui, X. Liu, J. Hou, Z. Wei, J. Liu, F. Liu, Biochar amendment increases C and N retention in the soil–plant systems: its implications in enhancing plant growth and water-use efficiency under reduced irrigation regimes of maize (*Zea mays* L.), J. Soil Sci. Plant Nutr. 23 (2023) 1576–1588.
[29] J. Lehmann, S. Joseph, Biochar for environmental management: an introduction, in: BC for Environmental Management, Sterling, London, 2015, pp. 1–13.
[30] E.O. Danso, A. Yakubu, Y.O.K. Darrah, E. Arthur, K. Manevski, E.B. Sabi, S. Abenney-Mickson, K. Ofori, F. Plauborg, M.N. Andersen, Impact of rice straw biochar and irrigation on maize yield, intercepted radiation and water productivity in a tropical sandy clay loam, Field Crops Res. 243 (2019) 107628.
[31] C. Li, Y. Xiong, Z. Qu, X. Xu, Q. Huang, G. Huang, Impact of biochar addition on soil properties and water-fertilizer productivity of tomato in semi-arid region of Inner Mongolia, China, Geoderma 331 (2018) 100–108.
[32] K. Shahzad, M. Abid, H.Y. Sintim, S. Hussain, W. Nasim, Tillage and biochar effects on wheat productivity under arid conditions, Crop Sci. 59 (2019) 1191–1199.
[33] C. Zhang, X. Li, H. Yan, I. Ullah, Z. Zuo, L. Li, J. Yu, Effects of irrigation quantity and biochar on soil physical properties, growth characteristics, yield and quality of greenhouse tomato, Agric. Water Manag. 241 (2020) 106263.
[34] O.T. Faloye, A.E. Ajayi, M.O. Alatise, B.S. Ewulo, R. Horn, Nutrient uptake, maximum yield production, and economic return of maize under deficit irrigation with biochar and inorganic fertiliser amendments, Biochar 1 (2019) 375–388.
[35] O.T. Faloye, M.O. Alatise, A.E. Ajayi, B.S. Ewulo, Effects of biochar and inorganic fertiliser applications on growth, yield and water use efficiency of maize under deficit irrigation, Agric. Water Manag. 217 (2019) 165–178.
[36] M. Paneque, M. José, J.D. Franco-Navarro, J.M. Colmenero-Flores, H. Knicker, Effect of biochar amendment on morphology, productivity and water relations of sunflower plants under non-irrigation conditions, Catena 147 (2016) 280–287.
[37] C. Bamminger, C. Poll, C. Sixt, P. Högy, D. Wüst, E. Kandeler, S. Marhan, Short-term response of soil microorganisms to biochar addition in a temperate agroecosystem under soil warming, Agric. Ecosyst. Environ. 233 (2016) 308–317.
[38] M.H. Zirgoli, D. Kahrizi, Effects of end-season drought stress on yield and yield components of rapeseed (*Brassica napus* L.) in warm regions of Kermanshah Province, Biharean Biol 9 (2015) 133–140.
[39] R.H. Lohaus, D. Neupane, M.A. Mengistu, J.Q.K. Solomon, J.C. Cushman, Five-Year field trial of eight *Camelina sativa* cultivars for biomass to be used in biofuel under irrigated conditions in a semi-arid climate, Agronomy 10 (4) (2020) 562.
[40] L.D. Metcalfe, A.A. Schmitz, J.R. Pelka, Rapid preparation of fatty acid esters from lipids for gas chromatographic analysis, Anal. Chem. 38 (1966) 514–515.
[41] J. Vollmann, T. Moritz, C. Kargl, S. Baumgartner, H. Wagentristl, Agronomic evaluation of camelina genotypes selected for seed quality characteristics, Ind. Crops Prod. 26 (2007) 270–277.
[42] B. Kirkhus, A.R. Lundon, J.E. Haugen, G. Vogt, G.I. Borge, B.I. Henriksen, Effects of environmental factors on edible oil quality of organically grown *Camelina sativa*, J. Agric. Food Chem. 61 (2013) 3179–3185.
[43] Y. Jiang, C.D. Caldwell, K.C. Falk, Camelina seed quality in response to applied nitrogen, genotype and environment, Can. J. Plant Sci. 94 (2014) 971–980.

[44] S.Y. Pan, C.D. Dong, J.F. Su, P.Y. Wang, C.W. Chen, J.S. Chang, H. Kim, C. P. Huang, C.M. Hung, The role of biochar in regulating the carbon, phosphorus, and nitrogen cycles exemplified by soil systems, Sustainability 13 (2021) 5612.

[45] G. Curaqueo, S. Meier, N. Khan, M. Cea, R. Navia, Use of biochar on two volcanic soils: effects on soil properties and barley yield, J. Soil Sci. Plant Nutr. 14 (2014) 911–924.

[46] M. Hussain, M.A. Malik, M. Farooq, M.Y. Ashraf, M.A. Cheema, Improving drought tolerance by exogenous application of glycinebetaine and salicylic acid in sunflower, J. Agron. Crop Sci. 194 (2008) 193–199.

[47] V. Yadav, T. Karak, S. Singh, A.K. Singh, P. Khare, Benefits of biochar over other organic amendments: responses for plant productivity (*Pelargonium graveolens* L.) and nitrogen and phosphorus losses, Ind. Crops Prod. 131 (2019) 96–105.

[48] F. Çığ, F. Sönmez, M.A. Nadeem, A.E. Sabagh, Effect of biochar and PGPR on the growth and nutrients content of Einkorn Wheat (*Triticum monococcum* L.) and post-harvest soil properties, Agronomy 11 (2021) 2418.

[49] N. Amiri-Darban, G. Nourmohammadi, A.H. Shirani-Rad, S.M.H. Mirhadi, I. Majidi-Heravan, Potassium sulfate and ammonium sulfate affect quality and quantity of camelina oil grown with different irrigation regimes, Ind. Crops Prod. 148 (2020) 112308.

[50] W. Diepenbrock, Yield analysis of winter oilseed rape (*Brassica napus* L.), Field Crops Res. 67 (2000) 35–49.

[51] K. Agboola, S.A. Moses, Effect of biochar and cowdung on nodulation, growth and yield of soybean (*Glycine max* L. Merrill), Int. J. Agric. Biol. 4 (2015) 154–160.

[52] M.C. Oguz, M. Aycan, E. Oguz, I. Poyraz, M. Yildiz, Drought stress tolerance in plants: interplay of molecular, biochemical and physiological responses in important development stages, Physiol. 2 (2022) 180–197.

[53] L.G. Angelini, L. Abou Chehade, L. Foschi, S. Tavarini, Performance and potentiality of Camelina (*Camelina sativa* L. Crantz) genotypes in response to sowing date under mediterranean environment, Agronomy 10 (12) (2020) 1929.

[54] S.S. Akhtar, G. Li, M.N. Andersen, F. Liu, Biochar enhances yield and quality of tomato under reduced irrigation, Agric. Water Manag. 138 (2014) 37–44.

[55] C. Wang, J. Hai, J. Yang, J. Tian, W. Chen, T. Chen, H. Luo, H. Wang, Influence of leaf and silique photosynthesis on seeds yield and seeds oil quality of oilseed rape (*Brassica napus* L.), Eur. J. Agron. 74 (2016) 112–118.

[56] M. Farooq, A. Wahid, N.S. Kobayashi, D.B. Fujita, S.M. Basra, Plant drought stress: effects, mechanisms and management, Sustain Agric (2009) 153–188.

[57] H. Jafari, G.H. Heidari, S.H. Khalesro, Effects of supplemental irrigation and biofertilizers on yield and yield components of Dryland wheat (Triticum aestivum L.), J Agri Sci Sustain Prod 29 (2019) 173–187.

[58] D. Neupane, J.K. Solomon, E. Mclennon, J. Davison, T. Lawry, Camelina production parameters response to different irrigation regimes, Ind. Crops Prod. 148 (2020) 112286.

[59] Z. Ahmed, J. Liu, E.A. Waraich, Y. Yan, Z. Qi, D. Gui, F. Zeng, A. Tariq, M. Shareef, H. Lqbal, G.H. Murtaza, Z.H. Zhang, Differential physio-biochemical and yield responses of *Camelina sativa* L. under varying irrigation water regimes in semi-arid climatic conditions, PLoS One 15 (12) (2020) e0242441.

[60] R. Aiken, D. Baltensperger, J. Krall, A. Pavlista, J. Johnson, Planting methods affect emergence, flowering and yield of spring oilseed crops in the U.S. Central High Plains, Ind. Crops Prod. 69 (2015) 273–277.

[61] A. Agarwal, O. Prakash, M. Bala, Effect of irrigation schedule on growth and seed yield of camelina (*Camelina sativa* L.) in Tarai region of central Himalaya, Oil Crop Sci 6 (2021) 8–11.

[62] Y. Sharghi, A.H. Rad, A.A. Band, G. Noormohammadi, H. Zahedi, Yield and yield components of six canola (*Brassica napus* L.) cultivars affected by planting date and water deficit stress, African J Biotechnol 10 (2011) 9309–9313.

[63] H.Y. Sintim, S. Bandopadhyay, M.E. English, A. Bary, J.E. González, J.M. DeBruyn, S.M. Schaeffer, C.A. Miles, M. Flury, Four years of continuous use of soil-biodegradable plastic mulch: impact on soil and groundwater quality, Geoderma 381 (2021) 114665.

[64] S. Angadi, W. Cutforth, G. McConkey, Y. Gan, Yield adjustment by canola grown at different plant populations under semiarid conditions, Crop Sci. 43 (2003) 1358–1366.

[65] M. Huang, Z. Zhang, Y. Zhai, P. Lu, C. Zhu, Effect of straw biochar on soil properties and wheat production under saline water irrigation, Agronomy 9 (8) (2019) 457.

[66] M.H. Sangtarash, M.M. Qaderi, C.C. Chinnappa, D.M. Reid, Differential sensitivity of canola (*Brassica napus*) seedlings to ultraviolet-B radiation, water stress and abscisic acid, Environ. Exp. Bot. 66 (2009) 212–219.

[67] Jr W.T. Schapaugh, J.R. Wilcox, Relationship between harvest indices and other plant characteristics in soybean, Crop Sci. 20 (4) (1980) 529–533.

[68] Y. Li, H. Tao, B. Zhang, S. Huang, P. Wang, Timing of water deficit limits maize kernel setting in association with changes in the source-flow-sink relationship, Front. Plant Sci. 22 (9) (2018) 1326, https://doi.org/10.3389/fpls.2018.01326.

[69] K. Ratajczak, H. Sulewska, G. Szymańska, New winter oilseed rape varieties-seed quality and morphological traits depending on sowing date and rate, Plant Prod. Sci. 20 (2017) 262–272.

[70] N. Bellaloui, A. Mengistu, M.A. Kassem, Effects of genetics and environment on fatty acid stability in soybean seed, Food Sci. Nutr. 4 (2013) 165–175.

[71] V. Dispenza, C. De Pasquale, G. Fascella, M.M. Mammano, G. Alonzo, Use of biochar as peat substitute for growing substrates of Euphorbia lomi potted plants, Span J Agric Res 14 (2016) e0908.

[72] K. Jemal, A. Abebe, Determination of bio-char rate for improved production of Lemmon grass (*Cymbopogon citratuc* L, Int J Adv Biol Biomed Res 4 (2016) 149–157.

[73] T. Suppadit, N. Phumkokrak, P. Poungsuk, The effect of using quail litter biochar on soybean (*Glycine max* [L.] Merr.) production, Chil. J. Agric. Res. 72 (2012) 244.

[74] A.K. Obour, E. Obeng, Y.A. Mohammed, I.A. Ciampitti, T.P. Durrett, J.A. Aznar-Moreno, C. Chen, Camelina seed yield and fatty acids as influenced by genotype and environment, Agronomy J 109 (2017) 947–956.

[75] A.D. Pavlista, G.W. Hergert, J.M. Margheim, T.A. Isbell, Growth of spring camelina (*Camelina sativa*) under deficit irrigation in western Nebraska, Ind. Crops Prod. 83 (2016) 118–123.

[76] M.F. Rodríguez-Rodríguez, A. Sánchez-García, J.J. Salas, R. Garcés, E. Martínez-Force, Characterization of the morphological changes and fatty acid profile of developing Camelina sativa seeds, Ind. Crop. Prod. 50 (2013) 673–679.

[77] H. Eyni-Nargeseh, M. Agha-Alikhani, A.H. Shirani-Rad, A. Mokhtassi-Bidgoli, S. A. Modarres-Sanavy, Late season deficit irrigation for water-saving: selection of rapeseed (*Brassica napus*) genotypes based on quantitative and qualitative features, Arch. Agron Soil Sci. 66 (2020) 126–137.

[78] S. Moradi, N.A. Sajedi, H. Madani, M. Gomarian, S. Chavoshi, Integrated effects of nitrogen fertilizer, biochar, and salicylic acid on yield and fatty acid profile of six Rapeseed cultivars, J. Soil Sci. Plant Nutr. 23 (2023) 380–397.