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Effect of Deficit Irrigation and Intercrop Competition on Productivity, Water Use Efficiency and Oil Quality of Chia in Semi-Arid Regions

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Abstract: Intercropping offers greater scope to introduce new crops. Cultivation of crops with diverse root architecture and different durations enhances the productivity of scarce resources like land and water. This study aimed to determine the effect of intercrop competition and irrigation regimes on yield, competition, land usage, irrigation water use efficiency (IWUE), and fatty acids of chia. The field experiment was conducted in semi-arid India during 2020–2022 with full (I_{100}) and deficit irrigation (I_{50}) and six intercrops. Results demonstrated that chia + fenugreek intercropping in I_{50} improved the crops' competitiveness, land equivalent ratio (LER) (1.77), land use efficiency (142.5%), and the IWUE of chia (23.2%). Notably, a chia + radish/spinach system in I_{50} reduced the seed yield (42.6–45.0%) of chia over I_{100} monocropping. A chia + fenugreek system in I_{50} resulted in a higher seed yield (196.2 kg ha^{-1}) than chia monocropping in I_{100}. Further, chia + fenugreek intercropping resulted in higher omega-3 content (56.68%) under I_{100}. Therefore, a chia + fenugreek system under I_{100} may be suggested over monocropping for better yield and oil quality. However, during water scarcity situations, growers can adopt a chia + fenugreek system under I_{50} which can give a similar chia equivalent yield and a higher LER and IWUE compared to chia monocropping under I_{100}.

Keywords: chia; intercropping; irrigation; land equivalent ratio; omega-3; water use efficiency

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1. Introduction

Chia (*Salvia hispanica* L.) is an annual herb belonging to the Lamiaceae family and is native to Southern Mexico and Northern Guatemala. Chia is emerging as a new industrial crop and is being cultivated in a few countries including Mexico, Guatemala, Columbia, Peru, Spain, Bolivia, Argentina, Austria, Germany, Netherlands, Paraguay, Brazil, and Australia [1]. Besides food usage, seeds and other products of chia are used in industrial applications such as stabilizers, emulsifiers or binders in the food industry, biodegradable films, anti-corrosive agents, health care products, cosmetics, biofuels, and pharmaceuticals [2]. Chia seeds are also a rich source of protein and oil (20.30 to 38.60%) with a highly balanced proportion of essential amino acids (α-linolenic acid) and polyunsaturated fatty acids (PUFA) compared to other vegetable oils [3,4]. Therefore, its seeds are among the highly exported commodities. Future market insights projected that the value of the chia seed market in the year 2023 reached USD 203 million. However, demand is expected to grow at a 7.0% cumulative average growth rate to boost the overall consumption value to USD 390.3 million (2023 to 2033) [5]. Chia was introduced to India in 2015 and has grown in pockets of states like Karnataka, Tamil Nadu, and Kerala. However, meeting the ever-increasing demand for chia seeds as a nutritive food for human consumption and a raw material for industry from the same piece of cultivable land and available resources is a highly challenging task [6].

The scope for horizontal expansion of cultivable areas is highly limited in the case of intensive cultivation of food crops. Therefore, introducing new industrial crops like chia with existing cropping patterns and better management practices offers opportunities to increase system productivity [7]. In this context, intercropping chia with prevailing crops promises to meet the diversified food needs of consumers and industrial demands and thus can improve land productivity, income, and the area under chia cultivation. Furthermore, Indian agriculture predominantly features small (1–2 ha) and marginal (<1 ha) farms with limited irrigation facilities for important cereals, pulses, vegetables, and other commercial crops [8]. Therefore, chia intercropping with prominent crops of local importance may be the best possible option in the semi-arid conditions of India. Intercropping improves system diversity due to the cultivation of more crops with different root architecture, canopy, duration, nutrients, and water requirements on the same piece of land [9,10]. In monocropping, most of the effective space remains vacant and soil moisture is more prone to evaporation losses, which reduce water productivity, especially during the lag phase of crop growth. Therefore, the initially available space, soil moisture, and light for chia can be effectively harnessed by growing short-duration leafy vegetables (30–50 days), which can fetch additional income for the farmer. This cropping system also offers security against crop losses due to uncertainties under monoculture [11]. However, there is a lack of information on the possibilities of integration of chia in cropping systems featured by spice and vegetable crops. However, previous studies have demonstrated the possibility of growing other industrial crops in intercropping systems such as dill + common bean [12], fennel + vegetables [13], linseed + *Lepidium* [14], peppermint + soybean [15], and barley + pea [16]. Notably, intercrops influenced the oil quality of crops in association; for instance, Rezaei-Chiyaneh et al. [17] found that fennel + common bean (3:2) intercropping recorded the highest essential oil and seed oil (fixed oil) content, unsaturated fatty acids (oleic and linoleic acids) in fennel seeds, and land equivalent ratio (1.32) on silty clay soils of Iran. Similarly, safflower + faba bean (1:1) intercropping achieved the highest LER, and quality of safflower in terms of palmitic acid, steric acid, oleic acid, and linoleic acid. Further, the system advantage (20–98%) is due to recovery made by intercrops [18].

The sustainability of agriculture demands conservation and judicious use of natural resources like water, which is a highly critical input for agricultural production and food security as irrigation accounts for ~80% of the total water usage. The lack of access to and the quality of irrigation facilities made crops more vulnerable to uncertainties leading to crop failures [19]. Thus, effectively utilizing limited irrigation water throughout the crop growth period to improve productivity per unit of water is a major challenge [20,21]. Systematically generated knowledge on irrigation requirements and water use efficiency (WUE) can guide decisions on water-saving strategies for industrial crops like chia in agro-ecologies featured by water scarcity. Though there are persistent efforts to augment knowledge on the water requirement of key food crops, very few attempts have been made to generate detailed information on irrigation requirements of chia-based intercropping systems. Previous studies demonstrated the varied response of chia seed yield and WUE under deficit irrigation [22]. It was also reported that 20% deficit irrigation (80% ETo) did not affect chia yield and the quality of fatty acids. Irrigated conditions showed a higher content of α-linolenic and other fatty acids with a lower oleic/linoleic ratio.

Meanwhile, irrigation on loamy soils negatively affected the antioxidant activity and total polyphenolic content of chia seeds [23]. Despite biomass and seed yield reduction in chia, deficit irrigation (40–70% of evapotranspiration ETo) improved the WUE for oil yield by 27%, and for omega-3 fatty acid (from 3.4 to 8.6 mg L^{-1}) on sandy loam soils [22]. Whereas severe water stress (40% potential evapotranspiration; PET) significantly reduced the oleic acid, linoleic acid, linolenic acid, and palmitic acid content in crops like sunflower (*Helianthus annuus* L.), safflower (*Carthamus tinctorius* L.), and sesame (*Sesamum indicum* L.) [24]. Similarly, deficit irrigation affected the seed, oil yield, WUE, the quality of nigella [25] and coriander [26], and also the productivity of olives [27] and banana [28].

Chia seeds are in high demand due to the high content of α-linolenic acid and metabolites of industrial and pharmaceutical interest [23]; hence, its cultivation is spreading even across resource-limited and less favorable agro-ecological regions. As of now, there is no information available on chia productivity and oil quality under varied irrigation regimes and potential intercropping options in the semi-arid climate of the Deccan Plateau (Agro-Ecological Region-6) of India, wherein short-duration vegetables are the main source of income for small and marginal farmers [29]. A long lag phase in the growth curve of chia offers spatial and temporal opportunities to accommodate other short-duration remunerative crops. Thus, we hypothesized that intercropping of short-duration vegetables during the initial stages under deficit irrigation can substantially improve land use efficiency, water productivity, and fatty acid composition of chia. In this context, a two-season field study was formulated to determine the effect of intercropping and deficit irrigation on crop competition, seed yield, oil quality, and resource use efficiency of chia with a focus on land use efficiency, WUE, and fatty acid composition.

2. Materials and Methods

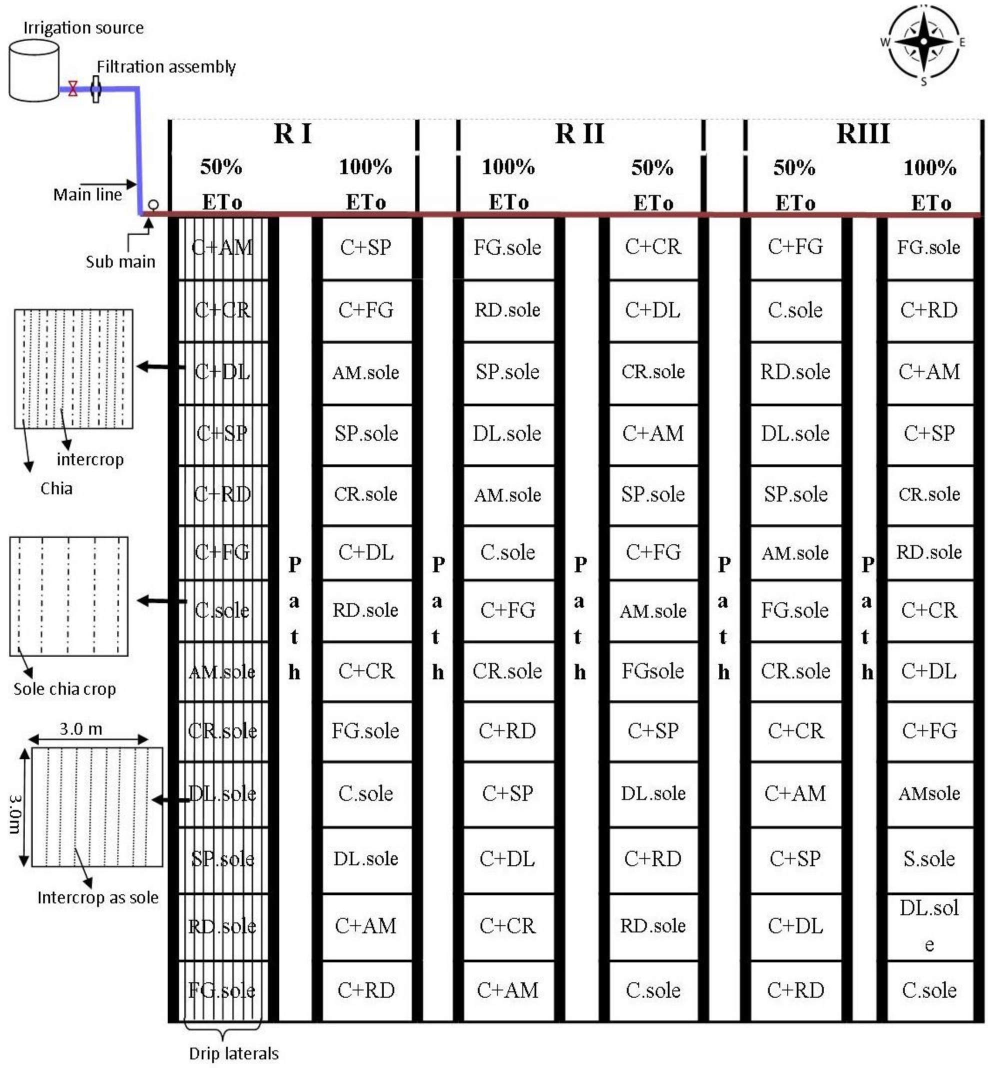
2.1. Weather and Soil of the Location

The field experiment was conducted for two consecutive winter seasons (2020–2021 and 2021–2022) at ICAR-National Institute of Abiotic Stress Management, Pune, Maharashtra, India (18°09′30.62″ N latitude and 74°30′30.08″ E longitude with an altitude of 570 m above mean sea level). The experimental location falls under the water scarcity zones in Deccan Plateau and is characterized by a hot and semi-arid climate [29]. The climate of the experimental site was typical semi-arid conditions with an annual average rainfall of 560 mm distributed mainly over four months from June to September, with short to long dry spells during the remaining period of the year. The average maximum temperature ranged from 29.5 to 30.7 °C with cumulative evaporation of 475.8–543.1 mm during the crop season. The weather parameters during the cropping period are depicted in Figure S1. The soil type of the experimental site was medium black, the bulk density of soil was 1.3 Mg m^{-3}, with field capacity (33.0%), permanent wilting point (17.0%), sand (11.8%), silt (18.8%), and clay (69.2%) contents as reported by Rajagopal et al. [30]. The pH, EC, and organic carbon content (0–20 cm depth) were 8.2, 0.2 dS m^{-1}, and 6.5 g kg^{-1}, respectively, at the beginning of the experiment. While available N, P_2O_5, and K_2O were 175.0, 7.9, and 180.0 kg ha^{-1}, respectively.

2.2. Experimental Details and Crop Management

The experiment was laid out in a split plot design with two irrigation regimes: deficit irrigation, I_{50} at 50% evapotranspiration (ETo), and full irrigation, I_{100} at 100% ETo were allotted to the main plots, and there were six intercrops (amaranthus (*Amaranthus tricolour* L.), coriander (*Coriandrum sativum* L.), dill (*Anethum graveolens* L.), spinach (*Spinacia oleracea* L.), radish (*Raphanus sativus* L. Domin), and fenugreek (*Trigonella foenum-graecum* L.)) with chia monocropping in subplots with three replications. The experimental layout is shown in Figure 1. One ploughing and two harrowing processes were performed to obtain the fine tilth and seed bed due to the small size of the seeds. All the intercrops were sown in the inter row spacing (60 cm) of the main crop (chia) at defined proportions (1:2) on 10th November 2020 and 2021. The seed rate and spacing of individual crops are presented in Table S1. The net plot size of the subplot was 3 × 3 m with 1.0 m buffer area, separated by an earthen bund to minimize the lateral movement of water and nutrients into adjacent plots. The whole main plot was installed with a surface drip irrigation system (Jain Irrigation

Systems Ltd., Jalgaon-425003, Maharashtra, India). The major nutrients ($N:P_2O_5:K_2O$) were applied as per the crop requirement through fertilizers [$CO(NH_2)_2$]:[$Ca(H_2PO_4)_2$]:(KCl), respectively (Table S1). As a basal dose, 100% (P_2O_5 and K_2O) and 50% of N were applied at the time of sowing. The remaining 50% N was applied to intercrops 20 days after sowing (DAS) as a top dressing. The weeds were managed periodically through manual hand weeding at 30 and 60 DAS.



C+AM, Chia+ Amaranthus; C.sole, Chia sole crop; C+CR, Chia+ Coriander; AM.sole, Sole Amaranthus; C+DL, Chia + Dill; CR.sole, Sole Coriander; C+SP, Chia + Spinach; DL.sole, Sole Dill; C+RD, Chia + Radish; SP.sole, Sole spinach; C+FG, Chia + Fenugreek; RD.sole, Sole Radish; FG.sole, Sole Fenugreek; ETo, Evapotranspiration

Figure 1. Experimental layout of chia based intercropping system under different irrigation levels.

2.3. Irrigation Scheduling

Irrigation was scheduled via a surface drip irrigation system with inline low-density polyethylene (LDPE) lateral pipes of 16 mm, and pressure-compensating drippers were spaced at 30 cm apart, with a discharge rate of 4 L h^{-1}. A total of nine lateral pipes were placed in each main plot, and crops were irrigated based on the most common cumulative pan evaporation approach at two levels (I_{50} and I_{100}). For the calculation of actual evapotranspiration (ETo), pan coefficient (Kp) of 0.7 of class A pan, U.S. Weather Bureau (USWB) was considered. Irrigation system (drip system) efficiency at a pressure of 1.2 g cc^{-1} was calculated by dividing actual discharge by specified discharge and expressed in %. Pressure in the subline was maintained at 1.2 g cc^{-1} for uniform discharge in both the treatments. Two common irrigations (total of 50 mm) were scheduled after sowing for the uniform germination and establishment of crops; later irrigations were scheduled as per the ETo approach. Details of irrigation days, the actual quantity applied, and rainfall during the crop growth period are given in Table 1. Irrigation was applied to the crops treatment wise when CPE reached 100% and 50% of ETo equivalent, and irrigation time was calculated using the following formula [31].

$$\text{Irrigation time (min)} = \frac{\text{Area}\left(\text{m}^2\right) \times \text{ETo}(\text{mm}) \times 60 \times \text{Irrigation system efficiency (\%)}}{\text{No. of emitters} \times \text{Emitter discharge (l/h)}} \quad (1)$$

Table 1. Total amount of water supplied during growing period (2020–2021 and 2021–2022).

Treatments	Water Applied (mm)		Common Irrigation (mm)	Rainfall (mm)		Total Water Supplied (mm)	
	2020–2021	2021–2022	2020–2021 & 2021–2022	2020–2021	2021–2022	2020–2021	2021–2022
I50 (at 50% ETo *)	145.2	132.7	50	10.6	20.0	205.8	202.7
I100 (at 100% ETo)	290.5	265.5	50	10.6	20.0	351.1	335.5
Number of irrigations (scheduled time; DAS *)	8 (7, 13, 20, 30, 41, 54, 60 & 69)	7 (10, 23, 32, 41, 54, 64 & 75)			-		

* ETo, evapo-transpiration; DAS, days after sowing; mm, millimeter.

2.4. Soil Moisture Measurement

Periodical soil moisture was recorded using the gravimetric method, and random soil samples were taken between crop plants in all the treatments on the next day of irrigation (9–10 a.m.) to realize the distribution in different treatments (Figure 2). Soil samples were drawn from surface depth (0–15 cm) at 10 cm away from the emitter using a screw auger. The groundwater level of the study area was 3 m below the ground surface.

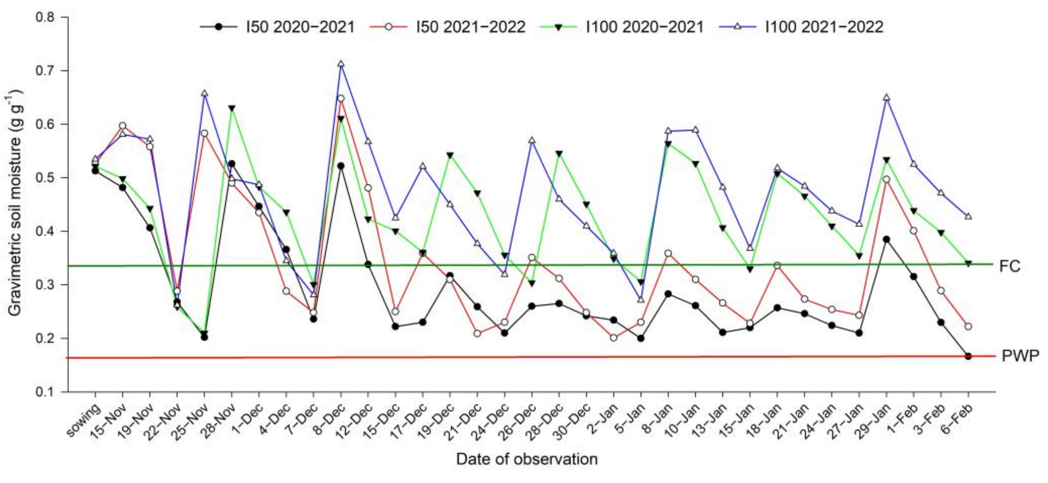


Figure 2. Soil moisture content during the crop growth period. I, irrigation; FC, field capacity; PWP, permanent wilting point.

2.5. Crop Growth and Canopy Attributes

Growth attributes such as plant height and biomass production of chia were recorded at 30, 60, and 90 DAS, while leaf area was measured at 30 and 60 DAS using a leaf area meter (LI-3100 leaf area meter, LI-COR. Inc., Lincoln, NE, USA) from five randomly tagged plants from each plot. The leaf area per plant was multiplied with crop geometry to obtain the leaf area index (LAI). Similarly, the normalized difference vegetation index (NDVI) was recorded at 60 DAS using a handheld Green Seeker Sensor (Trimble, SPL.Tech. Pvt. Ltd., Delhi, 110059, India). The crop canopy temperature of chia was recorded using a handheld infrared thermometer (Agri-therm III™, 6210 L, Everest Interscience Inc., Tucson, AZ, USA) before noon at 60 DAS [32].

2.6. Yield and Yield Attributes of Chia

Yield determinants like the number of spikes per plant and spike length were recorded at the time of harvest from the selected plants treatment wise. Then, seed yield was recorded from twenty selected plants, dried and threshed manually, and expressed in kg ha^{-1}. Later, the harvest index was calculated using the formula as followed by Harisha et al. [26].

$$\text{Harvest index} = \frac{\text{Seed yield}}{\text{Biomass yield}} \times 100 \quad (2)$$

2.6.1. Chia Equivalent Yield (CEY)

The yields of chia and vegetables in the intercropping systems were converted into CEY using the following formula [33].

$$\text{CEY}\left(\text{kg ha}^{-1}\right) = \text{Seed yield of chia} + \left(\frac{\text{Yield of vegetable} \times \text{Price of vegetable}}{\text{Price of chia}}\right) \quad (3)$$

2.6.2. Irrigation Water Use Efficiency (IWUE)

Treatment-wise IWUE for chia equivalent yield (CEY) was calculated during both seasons by considering chia equivalent yield and total water supplied [34]. The rainfall during the study periods (2020–2021 and 2021–2022) was considered for the calculation of total water supplied.

$$\text{IWUE for CEY}\left(\text{kg ha}^{-1}\text{mm}^{-1}\right) = \frac{\text{Chia equivalent yield (kg/ha)}}{\text{Total water supplied (mm)}} \quad (4)$$

2.7. Competition Indices

Different crop competition and land use indices were derived based on the proportion, duration, and economic yield of main and component crops, and monitory values.

2.7.1. Land Equivalent Ratio (LER)

The LER indicates the land area required by a sole crop to produce the same yield as that of an intercrop, thus measuring the efficiency of the production of crop mixtures compared with monocrops. LER was determined according to the formula suggested by Amanullah et al. [35].

$$\text{LER} = \frac{\text{Yab}}{\text{Ya}} + \frac{\text{Yba}}{\text{Yb}} \quad (5)$$

where Ya and Yb are the yields of chia and vegetables in pure stand, respectively, and Yab and Yba are the yield of chia and vegetables in intercropping, respectively.

If LER > 1 indicates the yield advantage of intercropping, and the reverse is true for LER < 1.

2.7.2. Area Time Equivalent Ratio (ATER)

ATER evaluates the performance of each crop in the intercropping system by considering its duration [36].

$$\text{ATER} = \left(\frac{\text{Y main crop}}{\text{Y sole crop}} \times \frac{\text{T main crop}}{\text{ti}}\right) + \left(\frac{\text{Y inter crop}}{\text{Y sole inter crop}} \times \frac{\text{T inter crop}}{\text{ti}}\right) \quad (6)$$

where 'T sole' is the duration of the growth cycle of the main crop; 'T intercrop' is the duration of the growth cycle intercrop; and 'ti' is the duration in days of the species with the longest growing period.

If ATER > 1 indicates the yield and time advantage of intercropping, a value <1 indicates the area and time disadvantage of intercropping.

2.7.3. Land Utilization Efficiency (LUE)

LUE indicates the percentage of land use in terms of duration, and it can be calculated using LER and ATER values [12].

$$\text{LUE} = \frac{(\text{LER} \times \text{ATER})}{2} \times 100 \tag{7}$$

If LUE > 100 indicates the advantage of the system, the reverse is true if LUE is <100.

2.7.4. Competition Ratio (CR)

The CR simply represents the ratio of the individual LER of the component crops in the system and considers the proportion in which the crops were sown [36].

$$\text{CR main crop} = \frac{(\text{LER main crop})}{(\text{LER inter crop})} \times \frac{\text{sown proportion of component b}}{\text{sown proportion of comonent a}} \tag{8}$$

where 'a' and 'b' denote main and intercrops, respectively.

If CR > 1 indicates the main (chia) is more competitive, CR = 1 indicates both crops are equally competitive, and CR < 1 indicates the intercrop is more competitive.

2.7.5. Aggressivity (A)

Aggressivity shows the relationship between dominant and dominated crop species when grown together. Indicates the relative yield increase in "a" crop relative to "b" crop in an intercropping system [37].

$$\text{A for main crop} = \left(\frac{\text{Yab}}{\text{Yaa}}\right) - \left(\frac{\text{Yba}}{\text{Ybb}}\right) \tag{9}$$

$$\text{A for inter crop} = \left(\frac{\text{Yba}}{\text{Ybb}}\right) - \left(\frac{\text{Yab}}{\text{Yaa}}\right) \tag{10}$$

where 'Yab' is the yield of the main crop in intercropping, and 'Yba' is the yield of intercrop crop and the proportion of intercrop in intercropping.

If A value is positive (+ve), it means the main (chia) crop is dominant, if A = 0, it indicates both crops are equally competitive, and if A is negative (−ve), it indicates the main (chia) crop is dominant.

2.8. Extraction and Estimation of Fatty Acids Composition in Chia Oil

The total oil content in chia seeds was extracted by grinding the cleaned and dried seeds. An amount of 10 g of powdered sample was weighed into the thimble and extracted with 150 mL of n-hexane for 3 h in Soxhlet apparatus in accordance with AOCS method Ba 3–38 [38]. The n-hexane was evaporated, and oil samples were stored at 4 °C for further analysis and fatty acid methyl ester (FAME) preparation. The oil content was expressed as % of seed (*w*/*w* basis). Total fatty acids and fatty acid composition were determined in the chia oil samples by preparing FAME according to AOCS method Ce 2–66 [39]. For this, 100 mg of oil samples were weighed in reaction vials and 1 mL of BF3-Methanol was added to the mixture. The reaction mixture was heated in sealed vials in a water bath at 60 °C for 30 min. To the cooled mixture, 3 mL of n-hexane was added to recover the methyl esters to the organic phase, then 1 mL of saturated NaCl was added. The aqueous and upper hexane layers were separated and anhydrous $NaSO_4$ was added to remove any moisture in the sample. The hexane was evaporated and stored at −20 °C until further analysis. During analysis, FAMEs were extracted with 1 mL of hexane. Diluted FAME was separated using Gas Chromatography Mass Spectroscopy (Shimadzu QP2020, Kyoto, Japan) equipped with an SH-Rtx-Wax column (30 m × 0.325 mm × 0.25 µm); a sample of 1 µL was used in split mode (10:1) with an autosampler. Helium was used as the carrier gas at a flow rate of 2.02 mL min^{-1}. The column temperature was programmed from 50 °C to 240 °C with an equilibrium time of 2.5 min, held for 35 min. Injector temperatures were set at 240 °C. The fatty acids were identified by a comparison of their retention indices, and their identification was confirmed by matching their mass spectra in the NIST-MS library.

2.9. Statistical Analysis

All data collected on various growth, yield, and quality parameters for two seasons were checked for normality before conducting an analysis of variance, and were later subjected to a combined analysis of variance (ANOVA) using the Mixed Model (proc GLIMMMIX, SAS v 9.3. SAS Institute, Inc., Cary, NC, USA) in split plot design with three replications. In this study's irrigation regimes, intercrops and seasons were considered as fixed effects and replications as random effects. The significant difference was tested using Tukey's least significance difference (LSD) test (α = 0.05). The overall analysis of variance (ANOVA) for the growth, yield, competitive indices, water use efficiency, and fatty acid composition of chia seeds in response to irrigation regimes and intercropping is presented in Table S2. Principle Component Analysis (PCA) and the biplot were derived based on two-way data to interpret the relationship between the key traits such as growth yield and quality parameters and compare the irrigation and intercropping treatments to discriminate the variability and relation.

3. Results

3.1. Crop Growth and Canopy Attributes

The irrigation levels and intercrops significantly ($p < 0.05$) influenced the growth attributes of chia such as plant height (Figure 3), dry biomass (Figure 4), and leaf area index; LAI (Figure 5). Deficit irrigation (I_{50}) reduced the plant height by 9.6, 14.4, and 11.0% at 30, 60, and 90 DAS, respectively, as compared to 100% irrigation (I_{100}). The reduction in LAI caused by deficit irrigation was 16.6 and 24.8% at 30 and 60 DAS, respectively, while the dry biomass production was reduced by 24.9, 18.8, and 24.8% at 30, 60, and 90 DAS, respectively, over I_{100}. As compared to chia monocrop, intercropping reduced the plant height of chia conspicuously at 90 DAS (4.8–17.4%) (Figure 3). Biomass yield and LAI followed a similar trend, with average reductions as high as 46.9% and 24.8%, respectively, at 90 DAS (Figures 4 and 5). Among intercrops, fenugreek outperformed others except for coriander, as indicated by relatively higher values for plant height (68.7 cm), LAI (1.55), and dry biomass (3295.3 kg ha^{-1}) of chia in the system. The reduction in plant height, LAI, and dry biomass of chia were significantly high in spinach (12.22, 21.95, and 41.48%, respectively) and radish (13.24, 21.95, and 42.40%, respectively) at 90 DAS compared to the chia + fenugreek system. Though the irrigation and intercrop interaction effect was significant, fenugreek as an intercrop outperformed spinach and radish both under I_{100} and I_{50}. Furthermore, the interaction of irrigation I_{100} plus chia monocropping achieved higher plant height (15.0, 69.2, and 74.3 cm at 30, 60, and 90 DAS, respectively), LAI (0.27 and 1.75 at 30 and 60 DAS, respectively), and biomass (65.8, 1262, and 4136 kg ha^{-1} at 30, 60, and 90 DAS, respectively). However, I_{100} with the chia + fenugreek system was recorded at par plant height, LAI, and next-best dry biomass.

Important canopy attributes such as the normalized difference vegetation index (NDVI) and canopy temperature (CT) were affected by deficit irrigation and intercropping in chia at 60 DAS (Table 2). As expected, chia plants grown with sufficient irrigation (I_{100}) had a higher NDVI (0.62) and lower CT (29.18 °C) than those grown with deficit irrigation (I_{50}). Likewise, chia monocropping recorded the highest NDVI (0.64) and the lowest CT (29.08 °C) followed by chia + fenugreek. Interaction effects due to irrigation and cropping systems revealed that there was a significant difference in the NDVI of chia among the intercrops under I50 but not under I_{100}. The NDVI of chia with fenugreek as an intercrop was significantly higher than that with spinach or radish as intercrops under I_{50} (Table 2).

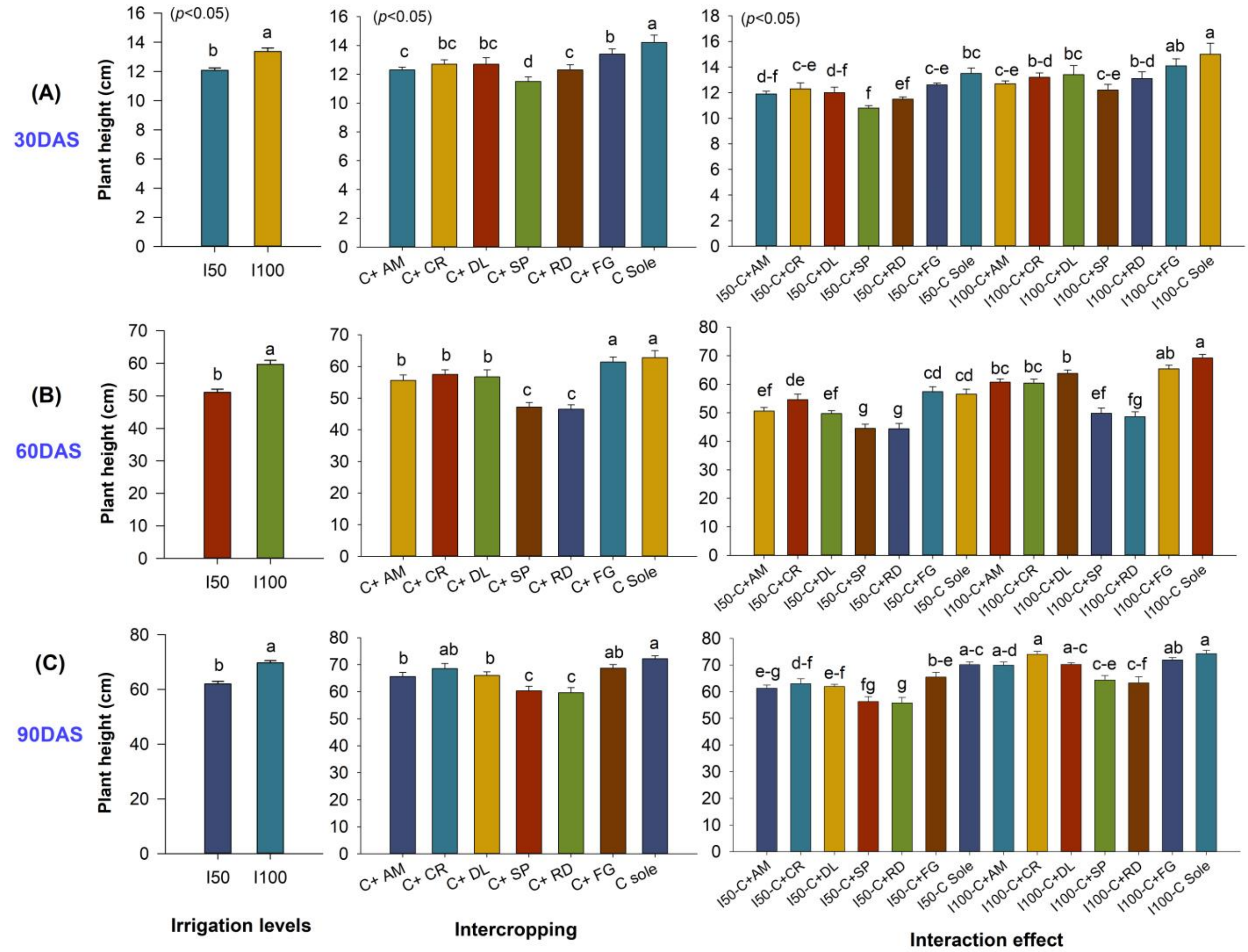


Figure 3. Plant height of chia in response to irrigation regime, intercropping, and their interaction effect at 30 DAS (**A**), 60 DAS (**B**), and 90 DAS (**C**). 50, 50% ETo; I100, 100% ETo; C + AM, chia + amaranthus; C + CR, chia + coriander; C + DL, chia + dill; C + SP, chia + spinach; C + RD, chia + radish; C + FG, chia + fenugreek; C Sole, chia monocrop. Type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; different letter in lower case above bar graph indicates significant difference among the treatments.

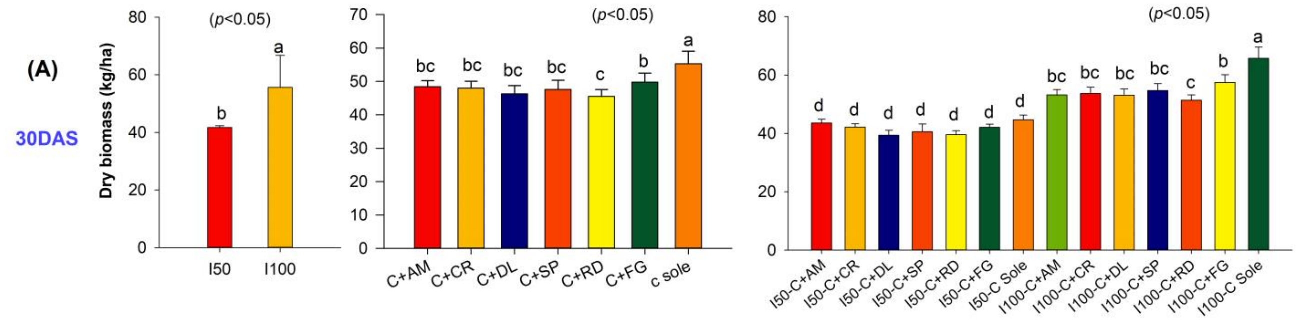


Figure 4. *Cont.*

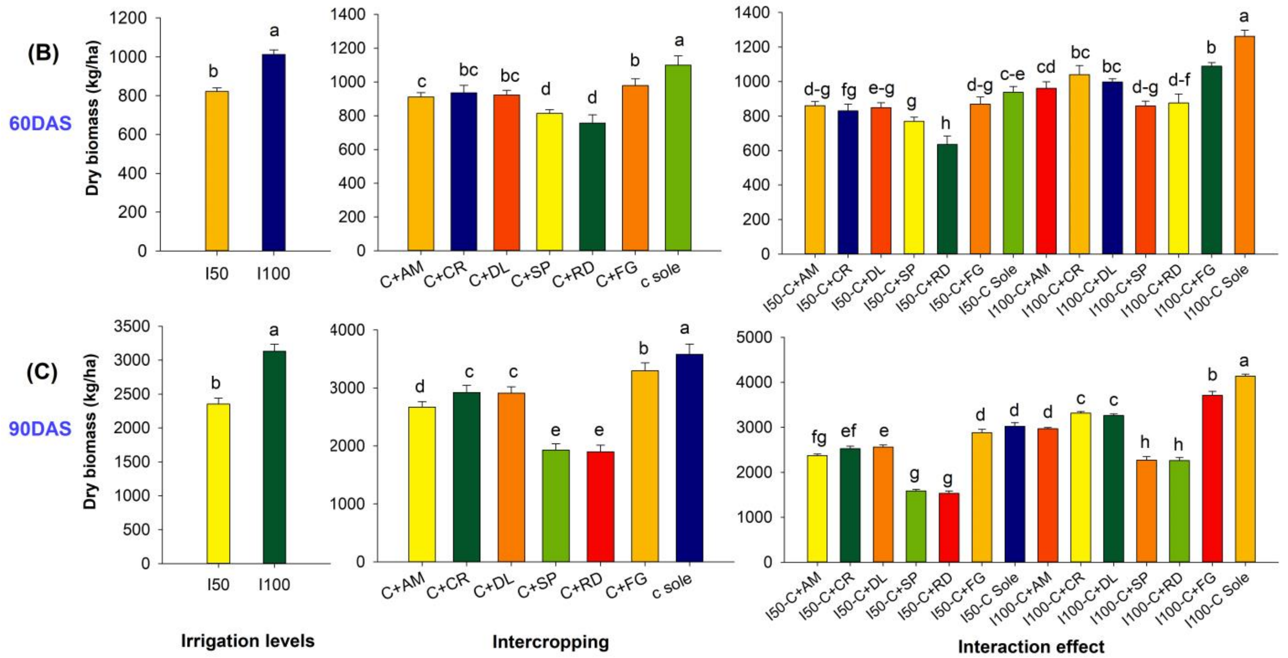


Figure 4. Biomass accumulation in chia as influenced by irrigation regime, intercropping, and their interaction effect at 30 DAS (**A**), 60 DAS (**B**), and 90 DAS (**C**). I50, 50% ETo; I100, 100% ETo; C + AM, chia + amaranthus; C + CR, chia + coriander; C + DL, chia + dill; C + SP, chia + spinach; C + RD, chia + radish; C + FG, chia + fenugreek; C Sole, chia monocrop. Type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; different letter in lower case above bar graph indicates significant difference among the treatments.

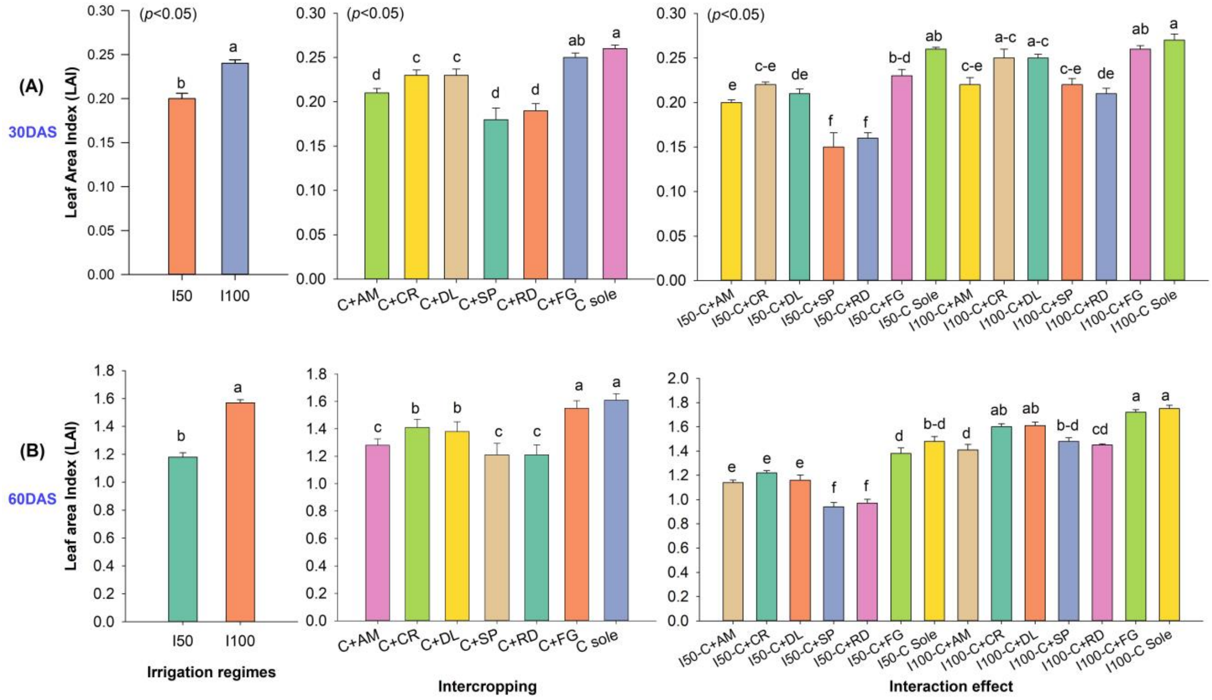


Figure 5. Leaf area index of chia as influenced by irrigation regime, intercropping, and their interaction effect at 30 DAS (**A**), 60 DAS (**B**). I50, 50% ETo; I100, 100% ETo; C + AM, chia + amaranthus; C + CR, chia + coriander; C + DL, chia + dill; C + SP, chia + spinach; C + RD, chia + radish; C + FG, chia + fenugreek; C Sole, chia monocrop. Type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; different letter in lower case above bar graph indicates significant difference among the treatments.

Table 2. Canopy and yield attributes of chia as influenced by irrigation and intercropping.

Treatments	NDVI *	Canopy Temperature (°C)	Number of Spikes per Plant	Spike Length (cm)	1000 Seed Weight (g)	Seed Yield (kg ha^{-1})	Harvest Index (%)	Oil Content (%)
Irrigation (I)								
I_{50} (50% ETo *)	0.54 b	30.3 b	15.8 b	14.8 b	1.17 b	525.2 b	23.12 a	34.17 b
I_{100} (100% ETo)	0.62 a	29.1 a	19.6 a	17.7 a	1.19 a	627.6 a	20.40 b	35.98 a
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)	9.8	2.9	15.2	12.6	1.2	12.6	8.8	3.6
Intercropping (IC)								
Chia + amaranthus	0.59 bc	29.7 ab	17.3 bc	15.6 cd	1.18 b	550.7 d	20.80 b	34.36 b
Chia + coriander	0.57 bc	29.6 ab	18.8 ab	16.8 bc	1.19 ab	604.2 bc	20.82 b	35.54 ab
Chia + dill	0.57 bc	29.8 ab	17.7 bc	16.1 c	1.18 ab	567.0 cd	19.63 bc	35.21 ab
Chia + spinach	0.54 d	30.2 b	14.8 d	14.6 d	1.18 b	498.2 d	26.30 a	33.87 b
Chia + radish	0.59 bc	30.4 b	15.7 cd	14.3 d	1.17 b	480.7 d	25.87 a	34.24 b
Chia + fenugreek	0.60 b	29.3 a	19.2 ab	17.7 ab	1.19 ab	628.2 b	19.12 c	35.54 ab
Chia monocrop	0.64 a	29.0 a	20.8 a	18.7 a	1.19 a	706.1 a	19.81 bc	36.77 a
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)	5.3	1.6	11.6	9.8	0.6	13.5	13.9	2.8
Year (Y)								
2020–2021	0.57 a	29.4 a	17.45 a	17.7 a	1.12 a	581.29 a	21.66 a	35.29 a
2021–2022	0.58 a	30.1 a	18.02 a	14.8 b	1.14 a	571.57 b	21.87 a	34.87 a
p value	NS	NS	NS	<0.0001	NS	0.026	NS	NS
CV (%)	-	-	-	12.6	-	1.2	-	-
Interaction (I × IC)								
I_{50}-chia + amaranthus	0.55 de	30.3 a–c	15.6 e–g	14.0 f–h	1.17 de	525.9 fg	22.22 bc	33.59 cd
I_{50}-chia + coriander	0.56 de	30.3 a–c	17.8 c–e	15.4 e–g	1.18 b–e	548.6 d–f	21.78 b–d	34.58 b–d
I_{50}-chia + dill	0.54 de	30.4 a–c	16.1 d–g	14.6 f–h	1.17 c–e	529.6 f	20.73 c–e	34.18 b–d
I_{50}-chia + spinach	0.49 f	30.9 ab	13.5 g	13.5 gh	1.17 de	455.7 gh	28.72 a	32.81 d
I_{50}-chia + radish	0.52 ef	31.0 a	14.1 gf	12.9 h	1.17 e	437.0 h	28.45 a	33.62 cd
I_{50}-chia + fenugreek	0.57 c–e	30.0 a–d	16.0 d–g	16.0 d–f	1.18 b–e	562.8 d–f	19.56 de	34.47 b–d
I_{50}-chia monocrop	0.58 b–d	29.8 a–e	18.0 c–e	17.1 c–e	1.18 b–e	617.3 cd	20.39 c–e	35.97 a–c
I_{100}-chia + amaranthus	0.58 b–d	29.3 c–e	18.9 c–e	17.1 c–e	1.19 a–e	575.5 d–f	19.37 de	35.14 a–d
I_{100}-chia + coriander	0.62 b	29.1 c–e	19.8 bc	18.2 a–c	1.19 a–d	659.8 bc	19.86 c–e	36.51 a–c
I_{100}-chia + dill	0.58 b–d	29.4 b–e	19.2 b–d	17.7 b–d	1.19 a–c	604.3 c–e	18.53 e	36.24 a–c
I_{100}-chia + spinach	0.61 bc	29.6 a–e	16.1 d–g	15.7 d–f	1.18 a–e	540.7 ef	23.88 b	34.94 a–d
I_{100}-chia + radish	0.61 bc	29.8 a–e	17.3 c–f	15.7 d–f	1.18 b–e	524.4 fg	23.29 b	34.87 a–d
I_{100}-chia + fenugreek	0.62 b	28.7 de	22.3 ab	19.4 ab	1.20 ab	693.5 b	18.67 e	36.60 ab
I_{100}-chia monocrop	0.69 a	28.4 e	23.7 a	20.3 a	1.21 a	794.9 a	19.22 e	37.57 a
p value	<0.0001	<0.0001	0.010	0.009	NS	0.0006	0.0002	NS
CV (%)	8.5	2.6	16.3	13.4	-	16.3	15.3	-

Means followed by the same letter, (s) within a column are not significantly differed. * ETo, evapotranspiration; NDVI, normalized difference in vegetation index; CV, coefficient of variance; type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; NS, non significant.

3.2. Yield Attributes, Seed Yield, and Chia Equivalent Yield (CEY)

The effects of irrigation and intercrops on yield attributes of chia were significant ($p < 0.05$), as illustrated in Table 2. The highest spike number, spike length, test weight, and seed yield were recorded for I_{100} (19.6, 17.7 cm, 1.19 g, and 627.6 kg ha^{-1}, respectively) and reductions in spike number, spike length, test weight, and seed yield caused by I_{50} were to the extent of 19.38%, 16.60%, 1.50%, and 16.31% respectively. However, I_{50} resulted in an 11.7% higher harvest index than I_{100}. The seed yield of chia with fenugreek (628.2 kg ha^{-1}) or coriander (604.2 kg ha^{-1}) as an intercrop was significantly higher than that with spinach (498.2 kg ha^{-1}) or radish (480.7 kg ha^{-1}), irrespective of the level of irrigation tested in the experiment, even though chia monocrop resulted in higher yield attributes. Whereas the harvest index of chia was reduced in chia monocropping (19.8) as compared to chia + radish (25.87) or spinach (26.30). Despite significant interaction effects of irrigation and intercrop on yield attributes, fenugreek complemented chia under both I_{50} and I_{100} in contrast to spinach and radish (Table 2). The oil content of chia seeds was influenced by the irrigation and intercropping treatments (Table 2). The highest oil content (35.98%) was obtained in I_{100} compared to I_{50}. Likewise, chia monocropping achieved higher oil content (36.77%) than the other intercropping systems. Interestingly, chia + fenugreek maintained comparable oil content (35.54%) compared to chia monocrop. At the same time, no significant difference was observed for oil content regarding the interaction of irrigation and intercropping. However, the value ranged between 32.81 and 37.57% (Table 2). System productivity measured as chia equivalent yield (CEY) resulted in 22.5% less yield for I_{50} compared to I_{100}. Adoption of chia + fenugreek intercropping realizes 26.4% higher CEY compared to chia monocrop (Table 3). Fenugreek as an intercrop in chia again proved best in achieving higher CEY by realizing 24.1 and 28.1% higher equivalent yield as compared to chia monocrop in I_{50} and I_{100}, respectively. The results highlighted that the same yield as chia monocrop in I_{100} can be achieved in a chia + fenugreek intercropping system, even with deficit irrigation (I_{50}).

Table 3. Crop equivalent yield (CEY) and competitive indices of chia due to irrigation regimes and intercropping.

Treatments	CEY (kg ha^{-1})	Land Equivalent Ratio	Land Use Efficiency	Competition Ratio	Area Time Equivalent Ratio	Agrresivity *
Irrigation (I)						
I_{50} (50% ETo)	747.4 b	1.57 a	129.6 a	1.71 a	1.01 a	0.85
I_{100} (100% ETo)	965.0 a	1.54 b	126.5 b	1.55 b	0.98 b	0.70
p value	<0.0001	0.0014	<0.0001	<0.0001	<0.0001	-
CV (%)	18.0	1.4	1.7	6.9	2.1	-
Intercropping (IC)						
Chia + amaranthus	651.8 e	1.57 c	131.2 b	1.88 b	1.06 b	1.10
Chia + coriander	886.9 c	1.64 a	136.1 a	1.97 b	1.08 b	1.20
Chia + dill	867.6 c	1.65 a	137.7 a	1.91 b	1.10 a	1.14
Chia + spinach	834.6 d	1.41 d	112.6 c	0.97 c	0.84 c	−0.03
Chia + radish	936.3 b	1.39 d	112.3 c	0.96 c	0.86 c	−0.05
Chia + fenugreek	959.8 a	1.70 a	138.3 a	2.11 a	1.07 b	1.33
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	-
CV (%)	12.8	8.4	9.6	32.1	11.8	-
Year (Y)						
2020–2021	859.1 a	1.60 a	132.5 a	1.61 a	1.04 a	0.79
2021–2022	853.3 a	1.50 b	123.6 b	1.65 a	0.96 b	0.77
p value	NS	<0.0001	<0.0001	NS	<0.0001	-
CV (%)	-	2.4	9.1	-	1.6	
Interaction (I × IC)						
I_{50}-chia + amaranthus	617.2 h	1.65 b	137.9 ab	1.99 bc	1.11 ab	1.23
I_{50}-chia + coriander	800.9 e	1.65 b	138.6 ab	2.12 ab	1.12 a	1.35
I_{50}-chia + dill	746.7 f	1.63 b	137.3 ab	1.99 bc	1.11 ab	1.22
I_{50}-chia + spinach	629.4 h	1.36 e	108.9 e	0.98 e	0.82 e	−0.03
I_{50}-chia + radish	876.7 d	1.37 e	112.2 de	0.96 e	0.87 e	−0.06
I_{50}-chia + fenugreek	813.5 e	1.77 a	142.5 a	2.23 a	1.08 a–c	1.43
I_{100}-chia + amaranthus	686.5 g	1.48 c	123.7 c	1.78 d	0.99 d	0.92
I_{100}-chia + coriander	972.8 c	1.63 b	134.3 b	1.82 cd	1.06 bc	1.05
I_{100}-chia + dill	988.6 c	1.67 b	138.0 ab	1.82 cd	1.10 a–c	1.07
I_{100}-chia + spinach	1039.8 b	1.46 cd	116.4 d	0.97 e	0.87 e	−0.04

Table 3. *Cont.*

Treatments	CEY (kg ha^{-1})	Land Equivalent Ratio	Land Use Efficiency	Competition Ratio	Area Time Equivalent Ratio	Agrresivity *
I_{100}-chia + radish	996.0 c	1.40 de	112.4 de	0.97 e	0.85 e	−0.04
I_{100}-chia + fenugreek	1106.2 a	1.63 b	134.2 b	1.99 bc	1.05 c	1.22
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	-
CV (%)	19.3	8.8	9.7	31.0	11.6	-

Means followed by the same letter(s) within a column are not significantly differed. ETo, evapo-transpiration; CV, coefficient of variance; type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; NS, non significant. * Statistical analysis not performed for aggressivity since it is denoted by sign viz., positive or negative.

3.3. Competition and Land Use Indices

To assess the competitiveness of the systems, the competition ratio (CR) and aggressivity (A) (Table 3) were estimated, and data revealed significant differences between the irrigation treatments and among the intercropping systems. The chia crop was more competitive and dominant under I_{50}, as indicated by a higher CR (1.71) and A (0.85) than for I_{100}, wherein the corresponding values were CR (1.55) and A (0.70). Irrespective of irrigation, in all intercropping systems except radish and spinach, chia was competitive and dominant, as indicated by CR >1 and positive aggressivity values. Whereas spinach and radish intercrops proved to dominate chia, as evidenced by CR < 1 (Table 3) and negative aggressivity values. Remarkably, chia + fenugreek (CR; 2.23 and A; 1.43) and chia + coriander (CR; 2.12 and A; 1.35) systems highlighted the higher competitive and dominating nature of chia over the intercrops under both I_{100} and I_{50}.

Similarly, land use indices like the land equivalent ratio (LER), area time equivalent ratio (ATER), and land utilization index (LUE) were significantly ($p < 0.05$) influenced by levels of irrigation (Table 3). Irrespective of intercrops, deficit irrigation led to the highest LER (1.57), ATER (1.01), and LUE (129.6) which were 1.91, 2.97, and 2.39% higher than I_{100}. Among intercrops, fenugreek, coriander, and dill were at par for LER (1.65–1.70) and LUE (136.1–138.3). With ATER values > 1, chia + dill (1.10), chia + coriander (1.08), and chia + fenugreek (1.07) were found to have an advantage over other intercrops which had ATER < 1. Further, spinach, and radish intercrops showed a relatively smaller advantage in terms of LER and LUE than fenugreek, coriander, and dill under both I_{50} and I_{100}.

3.4. Irrigation Water Use Efficiency (IWUE)

Irrigation and intercropping significantly influenced ($p < 0.05$) IWUE of chia with regard to CEY (Figure 6). The higher IWUE was recorded in I_{50} (3.66 kg ha^{-1}mm^{-1}) which was 23.2% higher than I_{100}. Intercropping of fenugreek or radish with chia improved the IWUE for CEY (3.60 kg ha^{-1}mm^{-1}) which was 29.72% higher as compared to chia monocrop. Further, chia + fenugreek and chia + coriander were found as the next best in terms of IWUE compared to chia monocrop. In the interactions of irrigation and intercropping, chia + fenugreek intercropping at I_{100} resulted in higher IWUE for CEY (3.21 kg ha^{-1}mm^{-1}), which was 31.1% higher compared to the I_{100} chia monocrop. Contrarily at I_{50}, chia + radish resulted in higher IWUE for CEY (4.30 kg ha^{-1}mm^{-1}). Thus, considering IWUE of the system as a whole on a CEY basis, the chia + fenugreek system outperformed other intercrops regardless of irrigation levels.

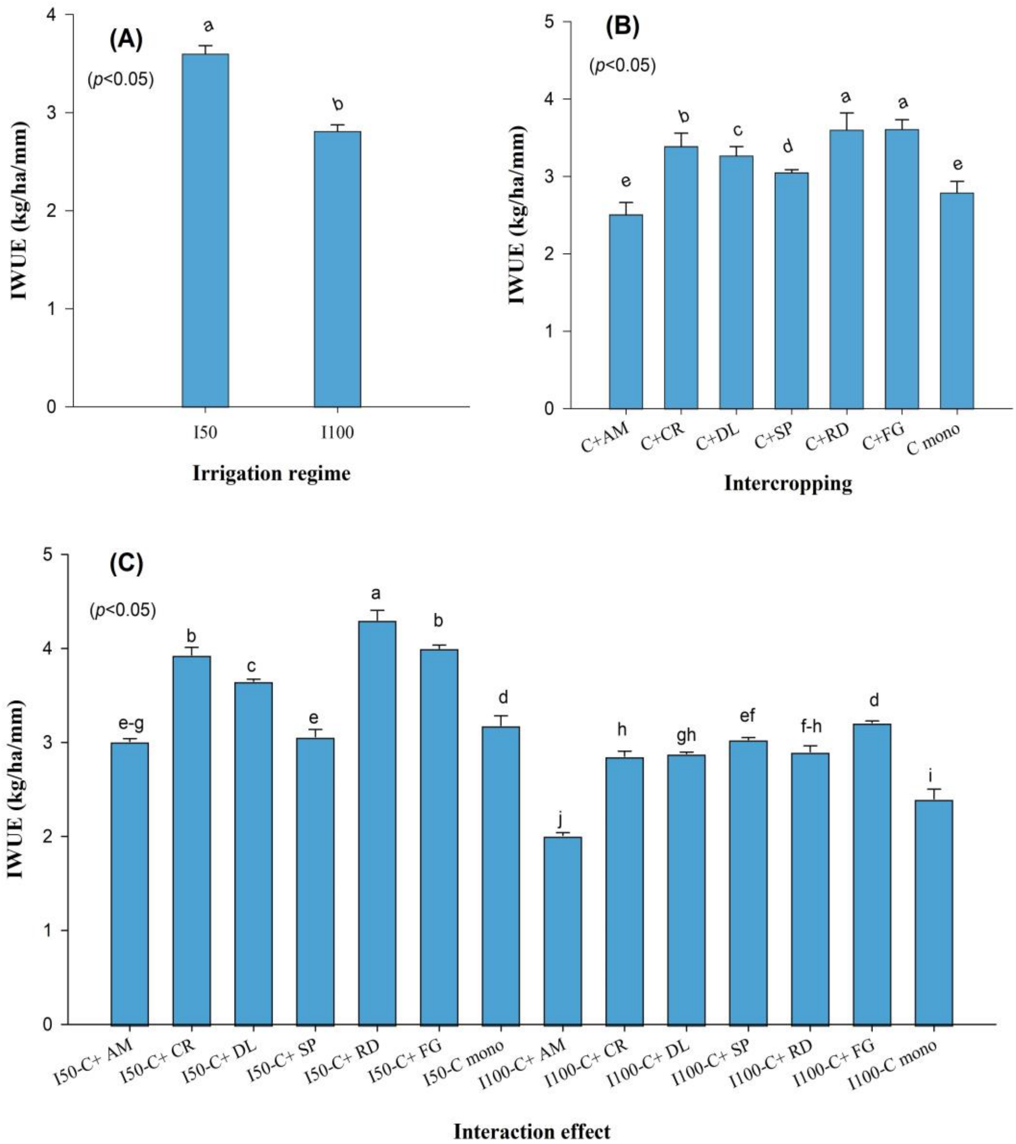


Figure 6. Irrigation water use efficiency (IWUE) for chia seed, oil, and α-linolenic acid (ALA) in response to irrigation regime (**A**), intercropping (**B**), and their interaction effect (**C**). I50, 50% ETo; I100, 100% ETo; C + AM, chia + amaranthus; C + CR, chia + coriander; C + DL, chia + dill; C + SP, chia + spinach; C + RD, chia + radish; C + FG, chia + fenugreek; C mono, chia monocrop. Type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; different letter in lower case above bar graph indicates significant difference among the treatments.

3.5. Fatty Acid Composition of Chia Seed Oil

The data revealed a wide range of values for various constituents of chia oil in response to the irrigation levels and intercropping system. The detailed composition of individual fatty acids is presented in Table 4. There was an increase in the α-Lenolenic acid (omega-3) and linoleic acid in I_{100} of 1.53 and 3.48%, respectively, as compared to I_{50}. However, I_{50} decreased oil quality due to an increase in palmitic acid to an extent of 8.02% compared to I_{100}. But the stearic acid content was not affected by irrigation. The intercrop competition significantly ($p < 0.05$) influenced fatty acid composition under different irrigation levels. The quality of chia oil in terms of α-Lenolenic acid (55.82%) was higher in intercropping of chia with fenugreek, which was at par with coriander, dill intercrop, and chia monocrop. Aggressive intercrops like spinach and radish reduced the α-Lenolenic acid by 3.6–4.4% compared to the chia + fenugreek system. Further, these aggressive intercrops increased the stearic acid and palmitic acid to an extent of 2.7 and 15.4%, respectively, compared to chia + fenugreek. Similarly, α-Lenolenic acid content was found to be higher in chia + fenugreek intercropping under both I_{50} (54.97%) and I_{100} (56.68%) which was comparable with chia monocropping at I_{100} (55.24%). These results indicate the beneficial effect of chia + fenugreek in maintaining high-quality chia oil in terms of α-Lenolenic acid under both irrigation levels.

Table 4. Fatty acid content of chia oil in response to irrigation regimes and intercropping.

Treatments	Palmitic Acid (%)	Stearic Acid (%)	Oleic Acid (%)	Linoleic Acid (%)	α-Lenolenic Acid (%)
Irrigation (I)					
I_{50} (50% ETo *)	9.72 a	4.77 a	8.69 a	22.96 b	53.83 b
I_{100} (100% ETo)	8.94 b	4.70 a	7.88 b	23.79 a	54.67 a
p value	<0.0001	NS	<0.0001	<0.0001	<0.0001
CV (%)	5.9	-	6.9	2.5	1.1
Intercropping (IC)					
Chia + amaranthus	9.53 ab	4.51 b	9.62 a	24.08 a	52.23 e
Chia + coriander	8.92 bc	4.52 b	8.44 b	22.97 c	55.12 ab
Chia + dill	5.57 c	4.60 b	8.39 b	24.05 a	54.36 bc
Chia + spinach	9.75 a	5.37 a	8.09 bc	22.96 c	53.81 dc
Chia + radish	9.76 a	5.17 a	8.40 b	23.34 b	53.32 d
Chia + fenugreek	9.48 ab	4.54 b	7.13 d	23.02 c	55.82 a
Chia monocrop	9.31 ab	4.44 b	7.91 c	23.21 b	55.11 ab
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)	16.8	7.9	9.8	2.1	2.3
Interaction (I × IC)					
I_{50}-chia + amaranthus	9.81 bc	4.89 bc	9.83 a	24.35 a	51.11 f
I_{50}-chia + coriander	8.86 cd	4.25 e–g	8.71 cd	22.46 f	55.38 ab
I_{50}-chia + dill	8.86 cd	4.33 ef	8.62 d	23.49 cd	54.68 b–e
I_{50}-chia + spinach	11.21 a	5.87	8.02 ef	21.31 g	53.57 de
I_{50}-chia + radish	10.79 ab	5.88 a	9.24 bc	22.23 f	51.85 f
I_{50}-chia + fenugreek	9.23 cd	3.92 g	8.15 de	23.72 bc	54.97 b–d
I_{50}-chia monocrop	9.30 cd	4.29 ef	8.26 de	23.15 e	54.98 b–d
I_{100}-chia + amaranthus	9.26 cd	4.14 fg	9.42 ab	23.81 b	53.36 e
I_{100}-chia + coriander	8.99 cd	4.80 b–d	8.17 de	23.48 cd	54.54 b–e
I_{100}-chia + dill	8.29 d	4.88 bc	8.17 de	24.60 a	54.05 c–e
I_{100}-chia + spinach	8.29 d	4.88 bc	8.17 de	24.60 a	54.05 c–e
I_{100}-chia + radish	8.73 cd	4.47 d–f	7.56 f	24.44 a	54.79 b–e
I_{100}-chia + fenugreek	9.73 bc	5.16 b	6.11 g	22.32 f	56.68 a
I_{100}-chia monocrop	9.32 cd	4.60 c–e	7.56 f	23.27 de	55.24 a–c
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)	9.0	12.5	11.0	4.3	2.7

* ETo, evapo-transpiration; CV, coefficient of variance; means followed by the same letter, (s) within a column are not significantly differed. Type of test, analysis of variance (split plot design); number of replicates, 3; level of significance, $p < 0.05$; NS, non significant.

3.6. Interrelationship between Traits as Influenced by Irrigation and Intercropping

Multivariate analysis was carried out to capture and explain the variability and associations among the various traits. PCA revealed that, out of ten principal components, PC1 and PC2 accounted for 78.3% of variability in the data set (Figure 7a). In PC1, SY, SL, NS, TW, biomass, and plant height have shown strong and positive association, as indicated by the narrow angle between the vectors. Based on length of the vectors, all these variables contributed more to the total variability. However, these traits have showed negative association with canopy temperature, as indicated by the wider angle of the vectors. In PC2, fatty acids like SA and PA were negatively associated with LA and ALA, whereas they were positively associated with CT (Figure 7b). Among the different parameters, the contributions of I_{100}, chia + fenugreek, and chia + coriander are higher than the other parameters in PC1. Whereas in PC2, the contributions of I_{50}-chia + radish and chia + spinach are higher (Figure 7c). From the PCA biplot, it was observed that I_{100}, chia + Fenugreek, and chia + coriander intercropping and chia monocrop were closely associated with higher values of NDVI, SY, TW, NS, SL, and ALA, while I_{50} chia + radish and chia + spinach negatively influenced the quality of oil in terms of higher PA and SA (Figure 7d).

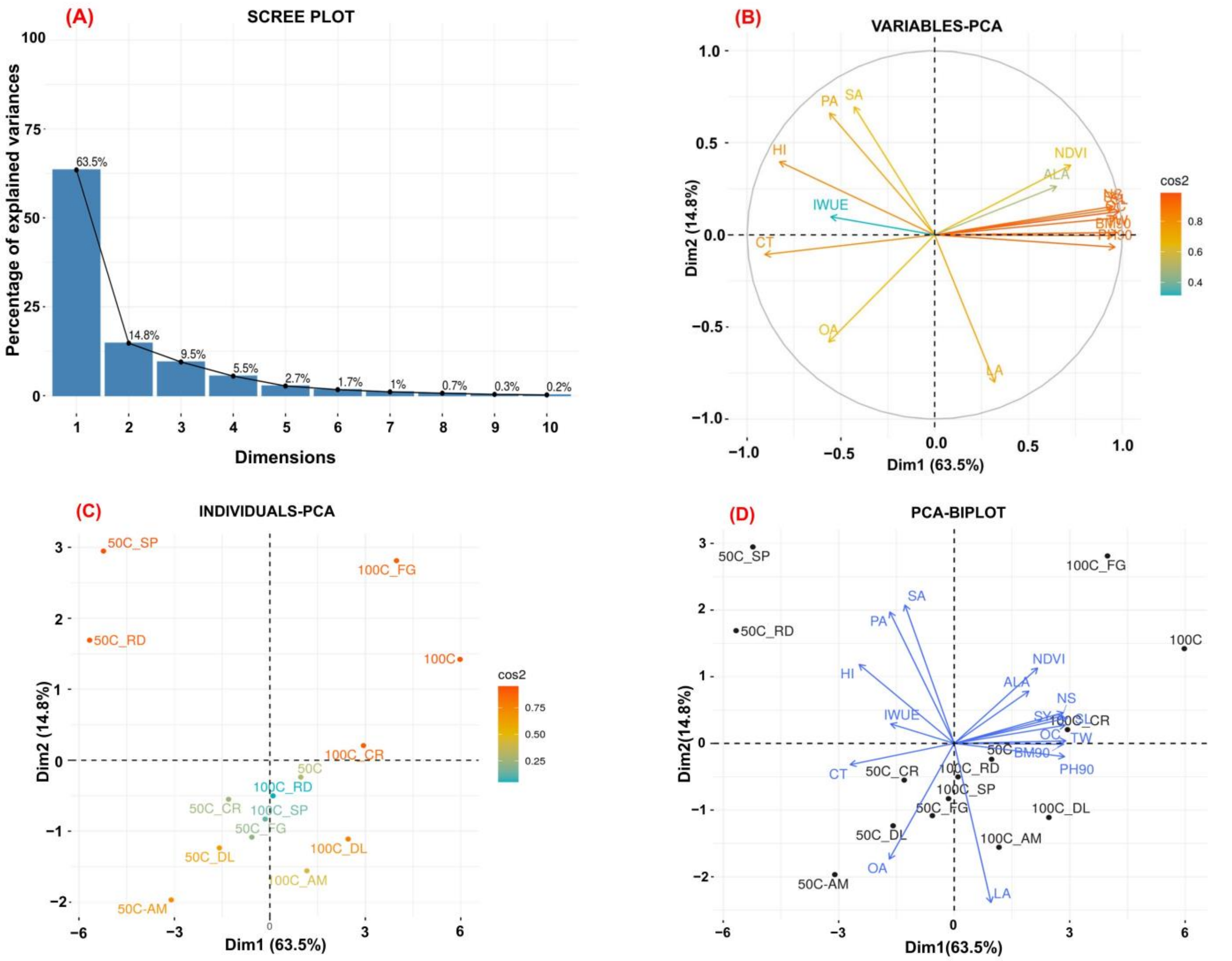


Figure 7. Principle Component Analysis (PCA) and character interrelationship of chia in response to irrigation regimes and intercropping. (**A**) Scree plot representing the variation in the principal component; (**B**) biplot of factor coordinates for PC1 and PC2 of the quantitative characters. (**C**) Scatter plot of the various treatment groups represented in two major principal components; (**D**) biplot represents the interrelationship between variables and treatment groups. 50; 50% ETo, 100; 100% ETo, C_AM; chia + amaranthus, C_CR; chia + coriander, C_DL; chia + dill, C_SP; chia + spinach, C_RD; chia + radish, C_FG; chia + fenugreek, C; chia monocrop. Plant height (PH90), biomass (BM90), seed yield (SY), oil content (OC), test weight (TW), number of spikes (NS), spike length (SL), canopy temperature (CT), normalized difference in vegetation index (NDVI), oleic acid (OA), palmitic acid (PA), stearic acid (SA), linoleic acid (LA), linolenic acid (ALA), irrigation water use efficiency (IWUE) under irrigation regimes (100 and 50% ETo) and intercroppings.

4. Discussion

Improving insights into the agronomy of crops like chia is crucial to enhancing profit for marginal farms as the demand for this crop is expected to grow at a 6.8% cumulative average growth rate [5]. Chia, as a potential industrial crop, can also play a key role in diversification in the areas dominated by a few traditional crops, which are less remunerative for marginal farms that are constrained by poor resources. Hence, the present investigation was oriented to generate much-needed knowledge on how to make chia cultivation viable in water-scarce environments in the Deccan Plateau of India which is featured by a vast stretch of semi-arid agro-ecologies with vertisols. This study was based on a prior report that indicated possibilities of growing chia in semiarid agro-ecologies [3]. The site chosen was ideal, with marginal rainfall and highly resource-poor soils that represent 59.5% of the area in the Deccan Plateau region. In the following sections, the effect of water deficit and intercrops on crop productivity in terms of seed yield, oil yield, and omega-3 yield have been discussed in addition to advantages of cropping systems in terms of WUE and land productivity.

4.1. Impact of Water Deficit on Crop Productivity

The deficit irrigation treatment (I_{50}) was effective in creating water stress during plant growth, as indicated by soil moisture depletion to an extent of 35–40% under I_{100}, which was sufficient enough to realize an adverse effect on plant growth and development. This was evident from a substantial reduction in grain yield of chia (16.3%) grown under I_{50} relative to I_{100}. The reduction in seed and oil yields could be attributed to a remarkable reduction in yield attributes such as the number of spikes, spike length, test weight of seeds, and oil content to an extent of 19.3%, 16.6%, 1.5%, and 5.03%, respectively. This drastic reduction (24.8%) in the biomass of chia due to deficit irrigation could be attributed to adverse effects of soil moisture deficit on key physiological processes such as transpiration and photosynthesis. Results obtained in the present study derive support from the previous reports on the reductions in biomass and seed yield of chia to an extent of 33.5% and 42%, respectively, when grown on sandy loam soil with irrigation restricted to 40% of ETo [22]. Substantial reductions in seed yield and oil content in response to water deficit have been reported in other oil-seed crops such as sesame, sunflower, and safflower [24]. Reductions in these physiological functions to an extent of 30% and 22%, respectively, were reported in chia grown in sandy loam soils of Northern Chile when the soil moisture deficit was 30 to 60%. In the present study, the reduction in oil yield and omega-3 yield of chia under I_{50} was due to a reduction in oil content and omega-3 content of seeds to an extent of 5.03% and 20.70% compared to I_{100}. During lipid biosynthesis, the main photosynthetic assimilate sucrose is converted into fatty acids, and this process is affected by deficit irrigation, thus inducing a reduction in oil content which is responsible for a lower oil yield [40]. Further, it can also be speculated that the elevated leaf tissue temperatures of chia due to soil moisture deficit might have affected fatty acid synthesis, as reflected by a close but inverse relationship between CT and omega-3 (ALA), as observed by us (Figure 7b) and also as reported in earlier studies [41]. Whereas, a positive linear relationship was observed between omega-3 (ALA) and NDVI values (Figure 7b). Our results agree with the findings of Herman et al. [22] that deficit irrigation (I_{40}) negatively influences the oil, omega-3, and linoleic acid content of chia. The yield losses in chia due to water deficit can be compensated greatly by appropriate strategies to improve crop and land productivity. It can be accomplished by leveraging spatial and temporal advantages offered by the lag phase of the growth curve of chia, which is relatively longer compared to that of other crops [41]; hences this provides sufficient scope for intercrops. One of the options for achieving this task is to accommodate short-duration and remunerative crops like vegetables as intercrops. However, deep insights into intercrop competition are needed to make a decision regarding an appropriate crop.

4.2. Impact of Intercrop Competition on Productivity of Chia

The adverse effect of deficit soil moisture on the productivity of a crop can be higher in an intercropping system than in monocrop due to severe competition for soil moisture and nutrients [39]. Earlier studies revealed that monocropping favors higher seed yield and oil content compared to intercropping due to a lack of competition in chia [42,43]. This corroborates with our findings that the chia + fenugreek or coriander systems were the best performers next to chia monocrop for seed yield (Table 2). The chia + fenugreek system substantially improved the seed yield to an extent of 22%. Our results on the advantage of growing legumes as intercrops draws support from previous reports by Xie et al. [44], Boori et al. [45] and Mahalakshmi et al. [46] wich show that the seed yield of fennel (*Foeniculum vulgare* Mill) and rice (*Oryza sativa* L.) was increased when intercropped with fenugreek, and coriander, respectively. While radish and spinach as intercrops drastically reduced the chia yield parameters such as seed oil and omega-3 content, this was supported by lower LAI, indicating a reduced photosynthetic surface area. Studies on the performance of chia with intercrops are not found in the literature; however, similar findings reported that the allelopathic effects of radish can affect the yield of component crops [47]. Further, the competition offered by spinach as an intercrop for soil moisture and nutrients especially under deficit irrigation due to aggressive root systems and rapid biomass accumulation affected the overall yield of chia [48]. Thus, the productivity and growth of chia reveal the advantage of crops like fenugreek or coriander over spinach or radish for intercropping. However, in addition to the yield, the quality of a product is also critical in fetching the premium price in the market; hence, an insight into this aspect of chia was given due attention in the present study.

4.3. Impact of Water Deficit and Intercrop Competition on Quality of Chia Oil

The quality of chia oil is determined by its composition and the presence of nutritionally rich proximate factors such as omega-3 fatty acid. Fatty acid composition in crop seeds is mainly governed by genetic factors; however, it can be altered to some extent by agronomic practices such as cropping patterns and deficit irrigation [49]. In response to deficit irrigation, there was an increase in stearic acid (SA), palmitic acid (PA), and oleic acid (OA) in chia seed oil. On the contrary, there was a reduction in linoleic acid (LA) and omega-3 with deficit irrigation (Table 4). Similar results regarding a reduction in omega-3 content in response to deficit irrigation were reported in chia [22,23] and sunflower [50]. A reduction in LA and omega-3 suggested that a possible thermal effect of deficit irrigation might have affected the activity of oleate desaturase enzymes involved in fatty acid synthesis, as observed in soybean [51]. Further, being a precursor of jasmonic acid, omega-3 must have been consumed in the stress-signaling process, as reported by Sánchez-Martín et al. [52] under water stress. A possible association between high canopy temperature and more saturated fatty acids such as fatty acid deterioration was also reported [53] in soybean and chia crop [31]. The data generated in the present experiment suggest that chia + fenugreek intercropping can produce quality oil in terms of oil content in seeds and omega-3 as well as in chia monocropping (Table 4). This beneficial effect of fenugreek intercropping may be due to relatively less competition, as indicated by the competition ratio and aggressivity estimated in the experiment. It can also be speculated that the enhanced availability of nutrients promotes the transformation of carbohydrates into oil, and thus improves the oil composition as well as resource utilization for photosynthesis [54,55]. In contrast, aggressive intercrops (radish and spinach) aggravated soil moisture stress, leading to an increase in the SA and PA content and a decrease in the LA and omega-3 content. As reported in previous studies, higher canopy and atmospheric temperatures during the seed filling stage reduced the PUFA and increased the oleic acid concentration in soybean [53]. Our study also confirmed this by revealing a higher canopy temperature of chia in intercropping with radish and spinach under both irrigation levels. This may be the first report on intercropping and its effect on the composition of fatty acids in chia seed oil. Subsequently, this might affect seed filling, the synthesis of fatty acids, and composition. Like fenugreek, short stature and shallow-rooted intercrops like coriander and dill did not affect the fatty acid content and composition of chia seed oil, indicating that these crops can also be used to enhance cropping system productivity under deficit moisture conditions.

4.4. Irrigation Water Use Efficiency (IWUE)

The crop yield per unit of applied water explains the IWUE, which has been extensively used to differentiate the management options [56]. In our study, deficit irrigation significantly improved the IWUE for chia (23.22%) relative to I_{100} (Figure 6). Despite a considerable yield reduction, higher IWUE in I_{50} was mainly due to reduced water application (40.5%). Our observations align with previous observations that biomass and seed yield per unit of water applied to the crop were high under deficit soil moisture in chia [22]. The increased IWUE under limited irrigation was attributed to a reduction in soil moisture loss and effective water uptake by the crops [56]. The IWUE of chia observed in the present study (2.5–3.5 kg $ha^{-1}mm^{-1}$) was comparable with that reported for sesame (2.60 kg $ha^{-1}mm^{-1}$) [57] but less than that recorded for safflower (4.40 kg $ha^{-1}mm^{-1}$) [58]. The advantage of having fenugreek as an intercrop in chia was highly evident from the significantly higher IWUE for seed yield (CEY basis) relative to the other intercropping systems tested (Figure 6). Further, fenugreek as an intercrop in chia maintained a higher IWUE than only radish in I_{50}. This might be associated with N-supplementing effects as well as less competition for moisture and nutrients from fenugreek, a leguminous and short-duration leafy vegetable crop that is harvested within 30 days after sowing. The improvement in crop yield and IWUE were partly attributable to the coordinated soil water sharing among the intercrops and the compensatory effect from the early-maturing fenugreek to the late-maturing chia [59]. A higher IWUE in intercropping under deficit irrigation was reported in peanut–sunflower, wheat–chickpea, and maize–pea [60–62]. Thus, our findings suggest that the advantage of improving IWUE under I_{50} can be realized only with suitable and compatible intercrops that determine crop yield under different levels of soil moisture.

4.5. Competitive and Land Use Indices

The benefits for farmers and the environment of sustainable cropping systems are assessed on the basis of yield equivalents and the resource use efficiency of a system. In this context, besides water, other key resources like land and time have been given due consideration. Hence, this study focused on the advantages offered by cropping systems in terms of LER, ATER, and LUE (Table 3). Interestingly, I_{50} enhanced the land use efficiency and competitive indices (LER > 1, ATER > 1, CR > 1, A positive, and LUE > 100), clearly indicating the higher competitive ability and dominance of chia under I_{50} than under I_{100}. This could be attributed to a greater reduction in the yield of sole crops under I_{50} as compared to I_{100}. The information on crop competition and LUE in deficit irrigation is meagre; however, Amanullah et al. [35] found that competition indices were higher under limited irrigation than with sufficient irrigation. The disadvantage of aggressive crops observed in our experiment corroborates previous reports that the high moisture and nutrient absorption capacity of intercrops such as spinach and radish could drastically reduce the LER under I_{50} irrigation [63]. The LER of the chia–fenugreek cropping system indicated that 70% more land is needed for chia sole crop to produce an equivalent yield.

Further, ATER provides a realistic comparison of the yield advantage of intercropping by considering the temporal advantage of the system. Higher ATER values (>1) of less aggressive intercrops in contrast to more aggressive crops like spinach and radish further supported the choice of a chia cropping system with crops like fenugreek and coriander as intercrops. The advantage of using leguminous crop for intercropping was evident from the greater ATER values in lupin–barley [64], mustard–pea, mustard–lentil, mustard–gram [65], and mint–soybean [15] systems. The CR and aggressivity (A) values of the chia–fenugreek system were >1 and positive, respectively, which were relatively higher than those of other systems, indicating an absolute yield advantage of fenugreek, which was dominated by chia, presumably due to better resource acquisition from the soil. Similar results of dominating behavior of crops when intercropped with legumes were reported in barley + vetch [66] and pea + cereal intercropping [67]. The LUE index was frequently used to explain the efficiency of a cropping system per unit area. As expected, the LUE of all intercropping systems was more than 100 under both irrigation regimes, indicating that the efficiency of intercropping is better than that of sole chia crop. In the current study, higher LER and ATER values for the chia + fenugreek system also resulted in higher LUE under deficit irrigation. This was possible due to better interception of solar radiation facilitated by time and space in the intercropping system. In earlier studies, Amanullah et al. [35], Liang et al. [16], and Barillot et al. [68] recorded LUE > 100 in intercropping with legumes due to less intercrop competition under a limited water supply. Thus, the present study provides sufficient evidence to suggest that the advantage of deficit irrigation in improving the WUE of the system can be realized with an appropriate choice of intercrop components based on key indicators like ATER, CR, and aggressivity. These indices revealed that non-aggressive crops like fenugreek, coriander, and dill can be better than aggressive crops like spinach and radish. This was mainly due to varying levels of competition in the acquisition of water and nutrients across the systems and nitrogen supplementation by legume crops if included in the system.

5. Conclusions

Water deficit drastically reduces the seed yield and quality of chia oil due to a reduction in omega-3 content. However, deficit irrigation enhances the IWUE (irrigation water use efficiency) by 23.22% for seed yield. The advantage of deficit irrigation in enhancing IWUE may result in a yield and quality penalty. This gap in yield loss can be bridged by an appropriate choice of intercrops, such as fenugreek, which provides additional yield and IWUE in chia with a 50% reduction in irrigation. Furthermore, intercropping of fenugreek under deficit irrigation harnesses spatial and temporal advantages, resulting in a greater land equivalent ratio, area–time equivalent ratio, and land use efficiency. Our study also provides evidence that the choice of aggressive and competitive intercrops, such as spinach and radish, can be unviable, as observed in the diminished performance of chia. Therefore, intercropping with fenugreek has an advantage over chia monocrop under well-watered or water deficit conditions in the vertisols of the Deccan Plateau regions of India.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10010101/s1, Table S1: Crops information and management practices; Table S2: Analysis of variance (ANOVA) for the growth, yield, competitive indices, water use efficiency, and fatty acid composition of chia seeds in response to irrigation regimes and intercropping; Figure S1: Monthly mean maximum and minimum temperature, relative humidity, total rainfall, and cumulative pan evaporation of the experimental location during cropping period (2020–2021 and 2021–2022).

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