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Strip Intercropping With Chickpea Supports Production of a Valuable Medicinal Oilseed

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ABSTRACT

Intercropping is prevalent in arid and semi-arid regions due to its high and stable productivity and efficient resource utilization. In this study, we evaluated the improving radiation use efficiency (RUE) and economic advantage in chickpea (*Cicer arietinum* L) and dragon's head (*Lallemantia iberica*) intercropping under an irrigation regime and sowing date. Field experiments were performed using a factorial split plot based on a randomized complete block design. The experimental treatments included irrigation systems at three levels: supplementary irrigation (irrigation after sowing and pre-flowering stage) (IS); complete irrigation as control (irrigation based on 20% depletion of available soil water) (I20), and deficit irrigation (irrigation based on 40% depletion of soil water) (I40); the second factor was the autumn sowing date (S1) and spring sowing date (S2), and the third factor was monocropping of chickpea (MC), monocropping of *L. iberica* (Ml), and intercropping of chickpea and *L. iberica* (In). The In (I20) treatment increased RUE in chickpea and *L. iberica* by 1.42 and 1.25 g/MJ, respectively, by extending the growth period. Intercropping proved more profitable than monocropping, with reduced irrigation needs and minimized drought stress during autumn and spring sowings. Chickpea exhibited a higher competitive ratio than *L. iberica*, indicating their dominance in the intercropping system, which was supported by the land equivalent ratio (LER) results. Adapting crop systems to local agroecological conditions is vital for enhancing resource efficiency and achieving sustainable agricultural outcomes. Based on this, intercropping these species shows promise in mitigating the negative impact of water and light limitations on crop yield.

1 | Introduction

Dragon's head, scientifically known as *Lallemantia iberica* (*L. iberica*), is an annual herbaceous plant resistant to dehydration (Abdolahi and Maleki Farahani 2019). It belongs to the Lamiaceae family and is native to a wide range of Eurasian regions, including Iran, the Middle East, China, Korea, and Manchuria (Rechinger 1982). This plant is a source of secondary metabolites, and its seeds contain mucilage, polysaccharides, fiber, oil, and protein (Zlatanov et al. 2012). *L. iberica* seed oil content (35%–38%) is higher than other oil seeds, and the most dominant fatty acid of *L. iberica* seed is linolenic acid, which is widely used in the pharmaceutical industry (Al-Snafi 2019). Some species of this genus also possess ornamental value and are used in landscape design (Rechinger 1982). Due to its drought tolerance and adaptability to semi-arid climates, *L. iberica* is considered a promising candidate for sustainable intercropping systems (Heydarzadeh

Abbreviations: CR, competitive ratio; CRc, chickpea competitive ratio; CRd, *L. iberica* competitive ratio; DAS, days after sowing; DM, dry matter; I20, irrigation based on 20% SAW (complete irrigation or control); I40, irrigation based on 40% SAW (low irrigation); In, intercropping of 50% chickpea:50% *L. iberica*; IS, irrigation in two stages including the sowing and pre-flowering stage (supplementary irrigation); LAI, leaf area index; LER, land equivalent ratio; MAI, monetary advantage index; Mc, monocropping of chickpea; Ml, monocropping of *L. iberica*; RUE, radiation use efficiency; S1, autumn sowing date; S2, spring sowing date; SAW, soil available water.

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et al. 2023). This plant is regarded as multipurpose due to its medicinal and industrial properties, as well as its role in agriculture (Jones and Valamoti 2005).

The common goal of farmers is to enhance crop productivity. The key to achieving sustainable agriculture likely lies in increasing the output per unit area and expanding arable land (Tsubo et al. 2003). To ensure high efficiency, it is important to follow optimum agricultural practices, like selecting suitable cropping systems that can utilize sunlight and land resources more efficiently (Raza, Feng, Iqbal, et al. 2019a).

Intercropping is an ancient agricultural practice of multiple cropping that involves sowing two or more crop species together in the same space and simultaneously (Chamkhi et al. 2022). Intercropping achieves greater light use complementarity per land area unit through crop mixtures with different rooting abilities, canopy structure, height, and nutrient requirements (Nyawade, Gachene, et al. 2019; Nyawade, Karanja, et al. 2019). Compared to monocropping, intercropping is advised to maximize resource consumption efficiency (Dwivedi et al. 2015) and foster interspecific interaction between component crops (Jalilian et al. 2017). The intercropping of legumes with non-legumes increases the photosynthetic capacity and the efficiency of using solar radiation, water, and nutrients (Brooker et al. 2015) compared to monocropping.

Chickpea (*Cicer arietinum* L) is one of the most important legume crops in the world (Department of Agriculture, Cooperation & Farmers Welfare 2018). This plant is also cultivated as a low-cost product and is used in rotation in the agricultural system of semi-arid tropical regions. Due to the ability of chickpea to adapt to a wide range of environmental and soil conditions (Singh 1997) and to fix atmospheric nitrogen in the soil, legumes provide soil fertility for the next crop (Choudhary et al. 2012). Hence, choosing the proper crop combination is crucial for productivity, as not all crops are compatible with intercropping (Malhotra and Singh 2017).

The intercropping of oilseeds with legumes can increase resource use efficiency compared to monocropping and improve crop yield (Hamzei and Babaei 2017). This approach is particularly advantageous in the context of climate change, where varying environmental conditions, such as increased drought stress, pose significant challenges to agricultural production (Thomas et al. 2007). By integrating legumes, which can fix atmospheric nitrogen and improve soil structure, intercropping systems can better withstand drought conditions and optimize water use. Additionally, adjusting the sowing date is a crucial management strategy to mitigate drought effects by aligning crop growth phases with favorable environmental conditions (Zhai et al. 2021). Early sowing, for instance, can extend the growing season, allowing crops to utilize residual soil moisture and establish a robust canopy earlier, thereby enhancing radiation use efficiency (RUE) and overall productivity (Zhang et al. 2019). According to previous reports, radiation absorption is directly related to temperature, and low temperatures can reduce the amount of radiation intercepted by plants (Ullah et al. 2019). Combining intercropping with optimal sowing date strategies can, therefore, create a synergistic effect, where the complementary resource use of intercropped species is maximized through strategic timing, ultimately improving resilience to climate change-induced drought stress. Furthermore, intercropping can improve light interception, and sowing date adjustments can optimize this by ensuring that the interception period coincides with higher radiation availability, thereby enhancing the overall efficiency and resilience of the agricultural system.

Despite the known benefits of intercropping legumes with oilseeds, limited information is available on the interaction between chickpea and *L. iberica* under arid conditions and variable irrigation and sowing dates. Therefore, this study aimed to evaluate the agronomic and economic performance of strip intercropping chickpea with *L. iberica* under different irrigation regimes and sowing dates in a semi-arid region of Iran.

2 | Materials and Methods

2.1 | Study Area

This research was performed in the 2021–22 and 2022–23 growing seasons at the Research Farm of Shahed University, Tehran, Iran (35.71′ N, 51.40′ E, altitude: 1190 m above the sea level). The climate of this region was arid and semi-arid, with an average annual precipitation of 250 mm and an average temperature of 17.2. Table 1 shows weather information including average temperature, monthly rainfall, relative humidity, and daily sunlight hours for the growing seasons of 2021–22 to 2022–23.

The results of the sampling and analysis of physicochemical characteristics of a composite soil sample (depth 0–30 cm) before the test are given in Table 2.

2.2 | Experimental Design

A field study was carried out using a factorial split plot based on a randomized complete block design with three replicates. The experimental factors included irrigation systems at three levels: (1) I20, Irrigation based on 20% SAW (Complete Irrigation or Control); (2) I40, Irrigation based on 40% SAW (Low Irrigation); (3) IS, Irrigation in two stages including the sowing and pre-flowering stage (Supplementary Irrigation); the second factor is the autumn sowing date (S1) (November 6) and spring sowing date (S2) (March 6), and the third factor is monocropping of chickpea (Mc), monocropping of *L. iberica* (Ml), and intercropping (In). In all treatments, Mc, Ml, and I were grown at a 0.25-m row distance. Each experimental unit was five meters long and two meters wide, with eight rows (Figure 1). Both cultivars of chickpea and *L. iberica* were seeded additionally, and then thinning was done to retain the sowing density of chickpea (cv. Ana) and *L. iberica* (cv. Sara) at 40 and 40 plants/m^2, respectively; the same density was used in Mc and Ml. The sowing and harvesting dates for chickpea and *L. iberica* under the autumn sowing date are November 6 and June 19, respectively. Similarly, the sowing and harvesting dates for chickpea and *L. iberica* under the spring sowing date are March 6 and June 19, respectively.

TABLE 1 | Monthly climatic data including rainfall, maximum and minimum temperatures, and relative humidity during the chickpea–*L. iberica* growing seasons (November to June) in 2021–2022 and 2022–2023 at the experimental site in Tehran.

	Year									
	2021–2022					2022–2023				
Month	Rainfall (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Relative humidity (%)	Sunshine (hr)	Rainfall (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Relative humidity (%)	Sunshine (hr)
November	13.0	18.2	4.3	53.1	162.0	4.0	28.0	6	56.5	162.3
December	24.0	17.4	3.0	46.8	299.0	3.6	20.0	2	49.2	298.6
January	5.0	11.4	2.4	53.6	296.8	12.8	11.0	−2	55.8	298.4
February	3.5	11.8	5.6	41.8	317.0	35.8	12.0	−2	56.3	325.9
March	16.2	17.1	9.1	37.9	325.0	13.5	26.0	3	51.9	304.0
April	1.3	23.6	14.3	22.1	406.4	18.6	29.0	7	43.4	395.1
May	2.0	28.1	19.5	26.8	427.0	1.4	34.0	9	29.5	428.3
June	0.0	34.4	26.6	12.9	769.0	9.8	39.0	18	26.9	435.7
Total	64.0					99.5				
Mean		20.3	11.9	41.5	375.2		24.9	5.1	46.9	331.0

TABLE 2 | Physicochemical properties of the soil at the experimental site prior to sowing in the 2021–2022 and 2022–2023 growing seasons.

Year	Soil texture	N (%)	Fe (mg Kg^{-1})	P (mg Kg^{-1})	O.C (%)	K (mg Kg^{-1})	Zn (ppm)	Cu (ppm)	Mn (ppm)	EC (dS M^{-1})	pH
2021–22	Loamy	0.14	5.66	8.62	0.57	378.8	2.7	4.28	6.48	5.21	7.60
2022–23	Loamy	0.08	4.86	8.42	0.55	373.2	2.5	4.2	6.42	5.19	7.25

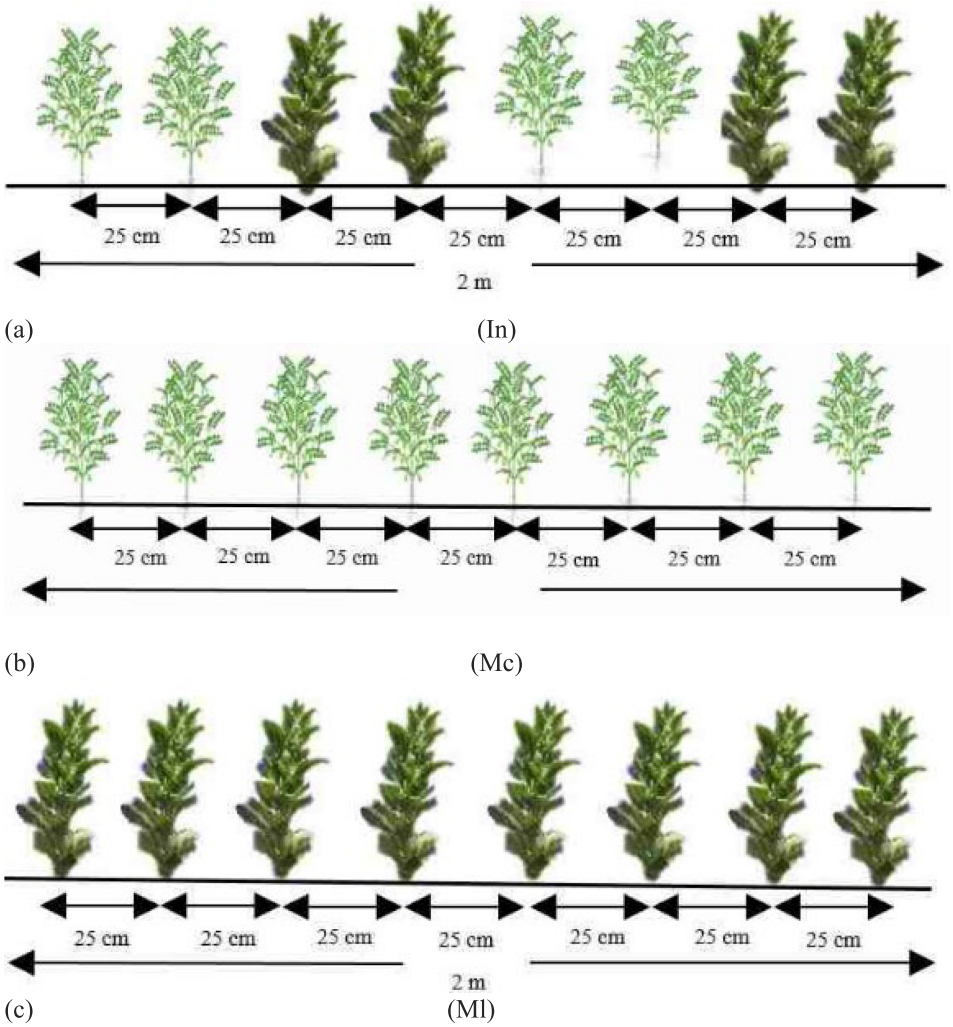

FIGURE 1 | Schematic representation of chickpea and *L. iberica* cropping systems used in the field experiment: (a) 50:50 intercropping (In), (b) monocropping of chickpea (Mc), and (c) monocropping of *L. iberica* (Ml).

2.3 | Irrigation Treatment

The irrigation regime treatment involved increasing the intervals between irrigations, which led to a greater depletion of soil available water before re-watering. A pressure plate device was used to measure field capacity (FC: 17.5%) and permanent wilting (PW: 6.5%). Plots were irrigated based on SAW (i.e., I20 and I40). The maximum allowable depletion (MAD) in the 0–30 cm soil layer was calculated using Equation (1) (Paravar et al. 2021).

$$\mathrm{MAD}\,(\%) = 100 \times (\mathrm{Fc} - \theta) / (\mathrm{Fc} - \mathrm{PWP}) \quad (1)$$

θ: pre-irrigation soil moisture; PWP: volumetric soil moisture at the permanent wilting point. To this end, samples were taken and weighed from the root zone soil taken 48 h after irrigation from a depth of 30 cm. After the soil samples were placed in an oven at 100°C for 24 h, the samples were re-weighed, and soil moisture content was determined. Therefore, irrigation was carried out when the soil moisture content in the control treatments (I20) and drought stress (I40) reached 15.3% and 13.1%, respectively, at a depth of 30 cm. The volume of water consumption for each plot was calculated according to Equation (2) (Mohammadi et al. 2019).

$$\mathrm{In} = (\mathrm{Fc} - \theta) \times \mathrm{D} \times \mathrm{A}) / 100 \quad (2)$$

In: Volume of water consumption for each plot, D: Indicates the depth of root expansion, A: Experimental plot area (10 m^2). Using the installed water meter, the water consumption of each plot was managed.

2.4 | Measured Traits

2.4.1 | Leaf Area Index

In both years, the leaf area index (LAI) of the two studied plants was measured every 2 weeks during the autumn growth season (120 DAS [leaf development], 135 DAS [flowering], 150 DAS [development of seed], 165 DAS [ripening of seed], and 180 DAS [senescence]) and spring growth season (30 DAS [leaf development], 45 DAS [flowering], 60 DAS [development of seed], 75 DAS [ripening of seed], and 90 DAS [senescence]). For the determination of LAI, five individual chickpea and *L. iberica* plants, respectively, were collected from each treatment. The "Biovis Leaf Area Meter (Expert Vision Labs Pvt Ltd, Mumbai, India)" was utilized to determine the leaf area of the sampled plants. Then, for each treatment, the LER is best interpreted as the relative land area needed by monocrops to produce the same yields as those obtained in a unit area of intercrop (Tang et al. 2008).

Chickpea and *L. iberica* individual plants were collected in a 1-m^2 area of every treatment at different growth stages: 120 DAS, 135 DAS, 150 DAS, 165 DAS, and 180 DAS of the autumn growth season, and 30 DAS, 45 DAS, 60 DAS, 75 DAS, and 90 DAS of the spring growth season. To investigate the dry matter (DM) of the sampled plants, they were manually harvested with shears and dried at 80°C to ensure constant weight. In order to analyze yields, chickpea and *L. iberica* plants from all treatments were collected from an area of 1 m^2 of the plot at the time of maturity. After drying and threshing, dried chickpea and *L. iberica* plants were weighed to measure their seed yield (kg ha^{-1}) for monocropping and intercropping.

2.4.2 | Radiation Use Efficiency

Based on the LAI and the quantity of light measured above and below the canopy by a "Lux meter (LUTRON-YK-1128SD, TAIWAN)" radiation extinction coefficient (K) was calculated separately for each cultivar using Beer–Lambert Equation (3) (Sinclair and Muchow 1999).

$$\ln \frac{I}{I_0} = -K \times LAI \tag{3}$$

I = the amount of light at the bottom of the canopy (MJ m^{-2}).

I_0 = the amount of light above the canopy (MJ m^{-2}).

Using the method provided by Goudriaan and Van Laar (2012), the amount of daily solar radiation at the geographical latitude of South Tehran was computed. Then, using Equations (4–6), the daily absorbed light for both species was determined (Tsubo et al. 2005). In order to change the total solar radiations to photosynthetic active radiation (PAR), the data of daily total solar radiation were multiplied by 0.5 (Rahman et al. 2017).

$$Iin = I0 \times 0.5\left(1 - \exp^{((-KcLc)+(-KlLl))}\right) \tag{4}$$

$$Il = Ii\left(\frac{(-KlLl)}{(KlLl) + (KcLc)}\right) \tag{5}$$

$$Ic = Ii - Id \tag{6}$$

Iin = Light absorbed by the intercropping canopy (MJ m^{-2}).

Ic = Light absorbed by the chickpea canopy (MJ m^{-2}).

Il = Light absorbed by the *L. iberica* canopy (MJ m^{-2}).

Kc = Radiation extinction coefficient of chickpea.

Kl = Radiation extinction coefficient of *L. iberica*.

Lc = Chickpea leaf area index.

Ll = *L. iberica* leaf area index.

In order to determine the RUE (g/MJ), the slope of the regression line between DM (g m^{-2}) and PAR (MJ m^{-2}) was calculated (Monteith 1972).

2.4.3 | Competition Characteristics

2.4.3.1 | Land Equivalent Ratio. To assess the seed yield advantage provided by intercropping, the land equivalent ratio (LER) was calculated using Equation (7) (Glaze-Corcoran et al. 2020).

$$LERt = \frac{Y\,In}{Y\,Mc} + \frac{Y\,Il}{Y\,Ml} \tag{7}$$

LERt: represent the total land equivalent ratio.

YIn: represents the yield of chickpea as intercrop.

YIl: represents the yield of *L. iberica* as intercrop.

YMc: represent the yield of chickpea as monocrop.

YMl: represent the yield of *L. iberica* as monocrop.

2.4.3.2 | Competitive Ratio Index. The Competitive ratio index (CR) is an important index for evaluating the competitiveness of species grown under intercropping. The chickpea competitive ratio (CRc) and *L. iberica* competitive ratio (CRd) index were calculated using Equations (8 and 9) (Willey and Rao 1980).

$$CRc = \frac{LERc}{LERl} + \frac{Zcl}{Zlc} \tag{8}$$

$$CRd = \frac{LERl}{LERc} + \frac{Zlc}{Zcl} \tag{9}$$

LERc is the chickpea ratio of species yield in intercropping to its yield in monocrop.

LERl is the *L. iberica* ratio of species yield in intercropping to its yield in monocrop.

Zcl is the proportion of species of chickpea in the intercropping.

Zlc is the proportion of species of *L. iberica* in the intercropping.

CR values of less than one indicate that a component in intercropping has fewer competitive effects and is considered a more suitable plant for intercropping (Willey and Rao 1980).

2.4.4 | Economic Analysis

2.4.4.1 | Monetary Advantage Index. To evaluate the economics of diverse sowing pattern treatments for chickpea and *L. iberica*, the monetary advantage index (MAI) was calculated using Equation (10) (Raza, Feng, van der Werf, et al. 2019).

$$\text{Monetary advantage} = \text{Value of both intercrops} \times \frac{\text{LER} - 1}{\text{LER}} \tag{10}$$

The value of both intercrops was determined using YilMl + YicMc, where Yil and Yic represent the average seed yield of *L. iberica* and chickpea, respectively, in intercropping, and Ml and Mc represent the current market value of *L. iberica* and chickpea in Iran in 2023 (current prices for *L. iberica* and chickpea are \$7.8284 and \$1.5536 kg, respectively).

2.5 | Statistical Analysis

The results of the 2 years were combined, analyzed by Bartlett test of homogeneity, and ensuring homogeneity of variances by factorial split plot based on a randomized complete block design. Therefore, the year was included as a factor in the combined analysis of variance, and the results for the two species, chickpea and *L. iberica*, were reported in (Tables S1–S6). Analysis of variance (ANOVA) was conducted with SAS Version 9.1 using the GLM method. The mean comparison was conducted using either the LSMEANS or PDIFF methods, and Excel was employed to plot the graphs.

3 | Results

3.1 | Leaf Area Index of Chickpea and *L. iberica*

During the growing season, the LAI of the *L. iberica* and chickpea initially increased, then steadied, and decreased in the final growth phases for all treatments. During both years of the study, the LAI of *L. iberica* and chickpea increased rapidly in all treatments from the 120 to 135 DAS stage for autumn sowing and the 30 to 45 DAS stage for spring sowing. The LAI peaked at 150 DAS for autumn and 60 DAS for spring sowing dates. The maximum LAI of chickpea under the autumn sowing date was observed in the In (I20) treatment, with an average of 1.62 over 2 years of study and examination. As compared to In (I20), there was a decrease of 27.1%, 26.5%, 12.9%, 39.7%, and 49.3% in the Mc (I20), Mc (I40), In (I40), Mc (IS), and In (IS) treatments (Figure 2a,b). Moreover, at the spring sowing date, it was lower by 39.5%, 29.6%, 38.2%, 45.4%, 53.8%, and 62.9% compared to the In (I20) treatment (Figure 2c,d).

The In (I20) treatment in the *L. iberica* had the highest LAI under the autumn sowing date, averaging 1.54. As compared to In (I20), there was a decrease of 16.2%, 5.1%, 2.5%, 46.2%, and 54.4% in the Mc (I20), Mc (I40), In (I40), Mc (IS), and In (IS) treatments (Figure 2e,f). In addition, at the spring sowing date, it was lower by 49.9%, 16.8%, 35.7%, 41.3%, 57.2%, and 66.9% compared to the In (I20) treatment (Figure 2g,h).

3.2 | Dry Matter of Chickpea and *L. iberica*

Due to the small size of the plants at the beginning of the growth period, no significant differences were observed in dry weight gain between different treatments over 2 years. Thus, from the 135 DAS (autumn) to 45 DAS (spring) stages (vegetative growth stage), the process of DM accumulation of *L. iberica* and chickpea entered the linear growth stage and increased quickly in all treatments. The maximal DM accumulation, physiological ripening of seeds, and pod drying occurred at stages 180 DAS (autumn sowing date) and 90 DAS (spring sowing date), which then displayed an almost consistent pattern. In this experiment over 2 years, for chickpea and *L. iberica*, treatment In (I20) under the autumn sowing date produced more DM than other treatments at different growth stages, with an average of 253.3 and 209 $g \cdot m^2$, respectively (Figure 3a–g).

3.3 | Seed Yield of Chickpea and *L. iberica*

The average chickpea and *L. iberica* seed yields in this study under different treatments showed that the In (I20) treatment had the maximum yield under an autumn sowing date in both years. Hence, the In (I20) treatment had the maximum yield of *L. iberica* (839 $kg\,ha^{-1}$) and chickpea (2922 $kg\,ha^{-1}$). When compared to the In (I20) treatment under the autumn sowing date, the yield of chickpea plants in the Mc (I20), Mc (I40), In (I40), Mc (IS), and In (IS) treatments decreased to 18.2%, 57.9%, 51.3%, 77.2%, and 83.0%, respectively. In addition, the seed yield was lower than the In (I20) treatment at the spring sowing date by 48.5%, 43.1%, 73.0%, 68.7%, 87.6%, and 88.4%, respectively (Figure 4a,b).

While a similar trend was observed for the yield of *L. iberica* seeds, as compared to In (I20), there was a decrease of 18.1%, 33.1%, 23.1%, 63.2%, and 77.2% in the Mc (I20), Mc (I40), In (I40), Mc (IS), and In (IS) treatments, respectively. In addition, the seed yield was lower than the In (I20) treatment at the spring sowing date by 22.2%, 13.8%, 75.8%, 72.7%, 92.9%, and 95.4%, respectively (Figure 4c,d).

Regardless of the Mc (IS) treatment, grain yields under the Mc (I20) and Mc (I40) treatments decreased by 18.2% and 13.6%,

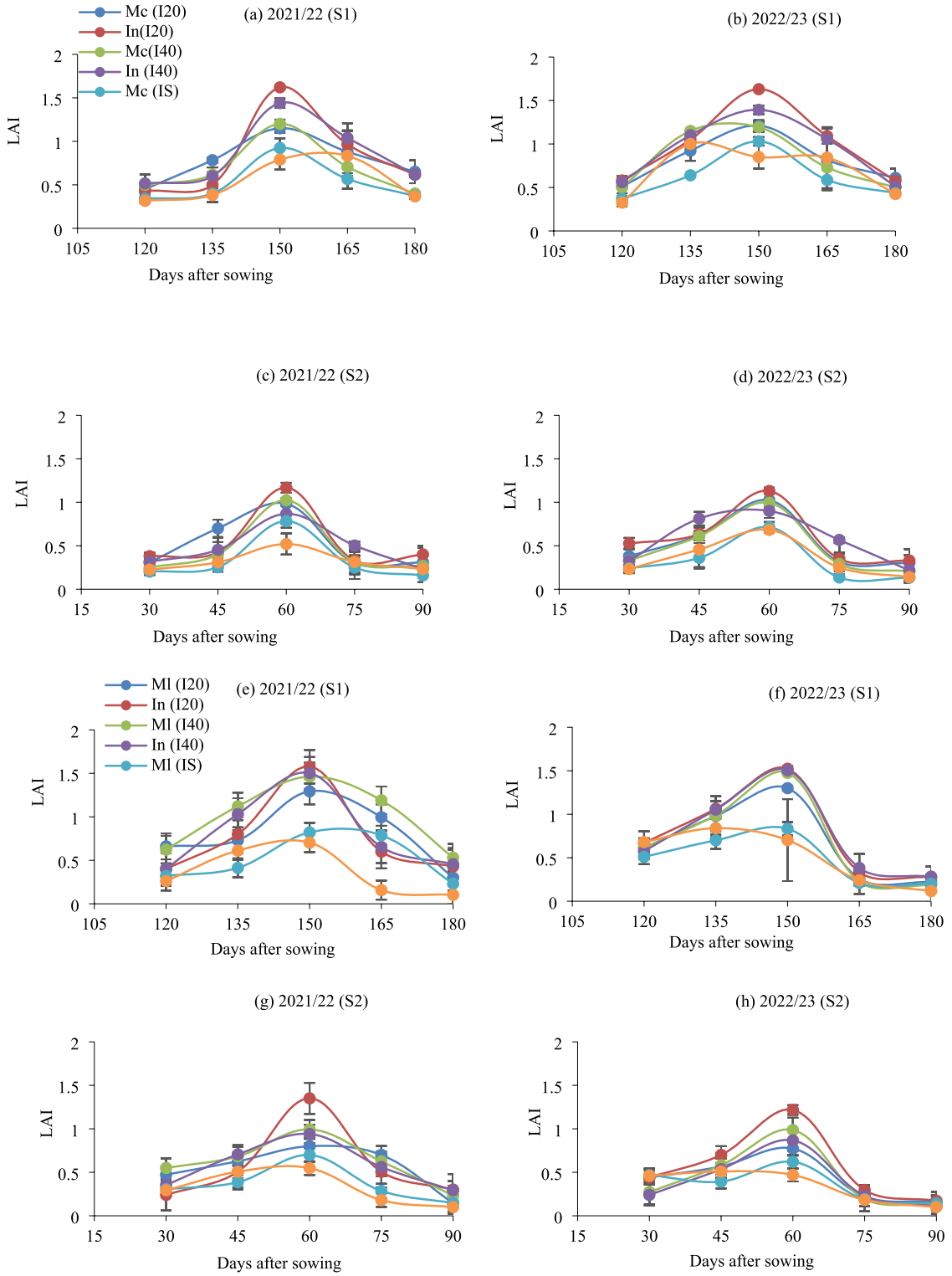

FIGURE 2 | Leaf area index (LAI) of chickpea (a–d) and *L. iberica* (e–h) under different cropping systems, sowing dates, and irrigation regimes during the 2021/22 and 2022/23 growing seasons at the experimental site. Mc: mono-cropping of chickpea; Ml: mono-cropping of *L. iberica*; In: intercropping of 50% chickpea: 50% *L. iberica*; S1: autumn sowing date; S2: spring sowing date; I20: complete irrigation or control (irrigation based on 20% SAW); I40: Low irrigation (irrigation based on 40% SAW); IS: Supplementary irrigation (irrigation in two stages including the sowing and pre-flowering stage). Bars at each data point represent the standard deviation of the mean ($n = 3$).

respectively, during the autumn sowing date, and by 9.5% and 13.8% during the spring sowing date, compared to the In (I20) and In (I40) treatments (Figure 4a,b). Similarly, regardless of the Ml (IS) treatment, grain yields under the Ml (I20) and Ml (I40) treatments decreased by 10.9% and 8.9%, respectively, during the autumn sowing date, and by 3.2% and 4.4% during the spring sowing date, compared to the In (I20) and In (I40) treatments. The In (IS) treatment during the spring

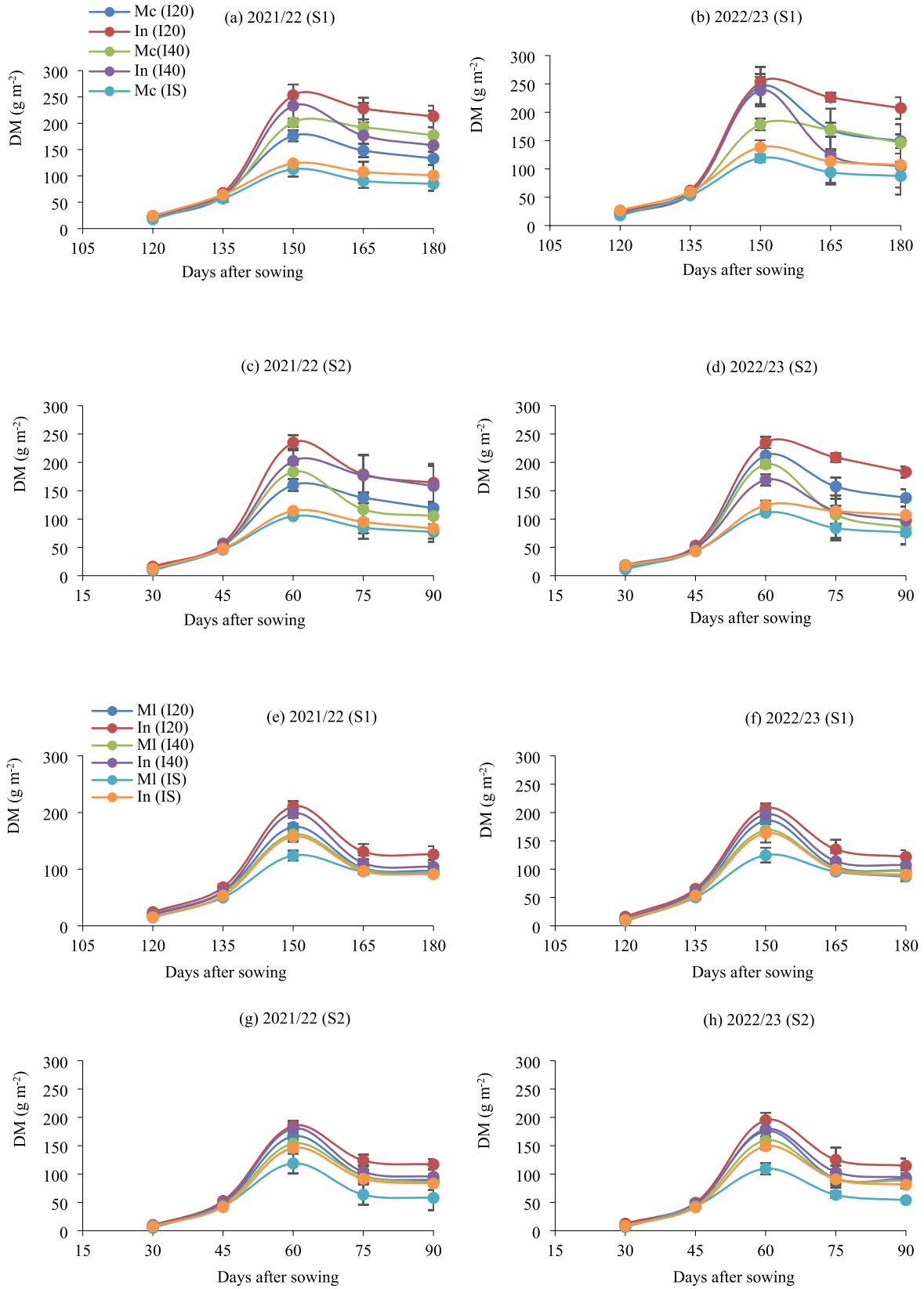

FIGURE 3 | Dry matter (DM) accumulation of chickpea (a–d) and *L. iberica* (e–h) under different cropping systems, sowing dates, and irrigation regimes during the 2021/22 and 2022/23 growing seasons at the experimental site. Mc: mono-cropping of chickpea; Ml: mono-cropping of *L. iberica*; In: intercropping of 50% chickpea: 50% *L. iberica*; S1: autumn sowing date; S2: spring sowing date; I20: complete irrigation or control (irrigation based on 20% SAW); I40: Low irrigation (irrigation based on 40% SAW); IS: Supplementary irrigation (irrigation in two stages including the sowing and pre-flowering stage) is based on 20% SAW. Bars at each data point represent the standard deviation of the mean ($n = 3$).

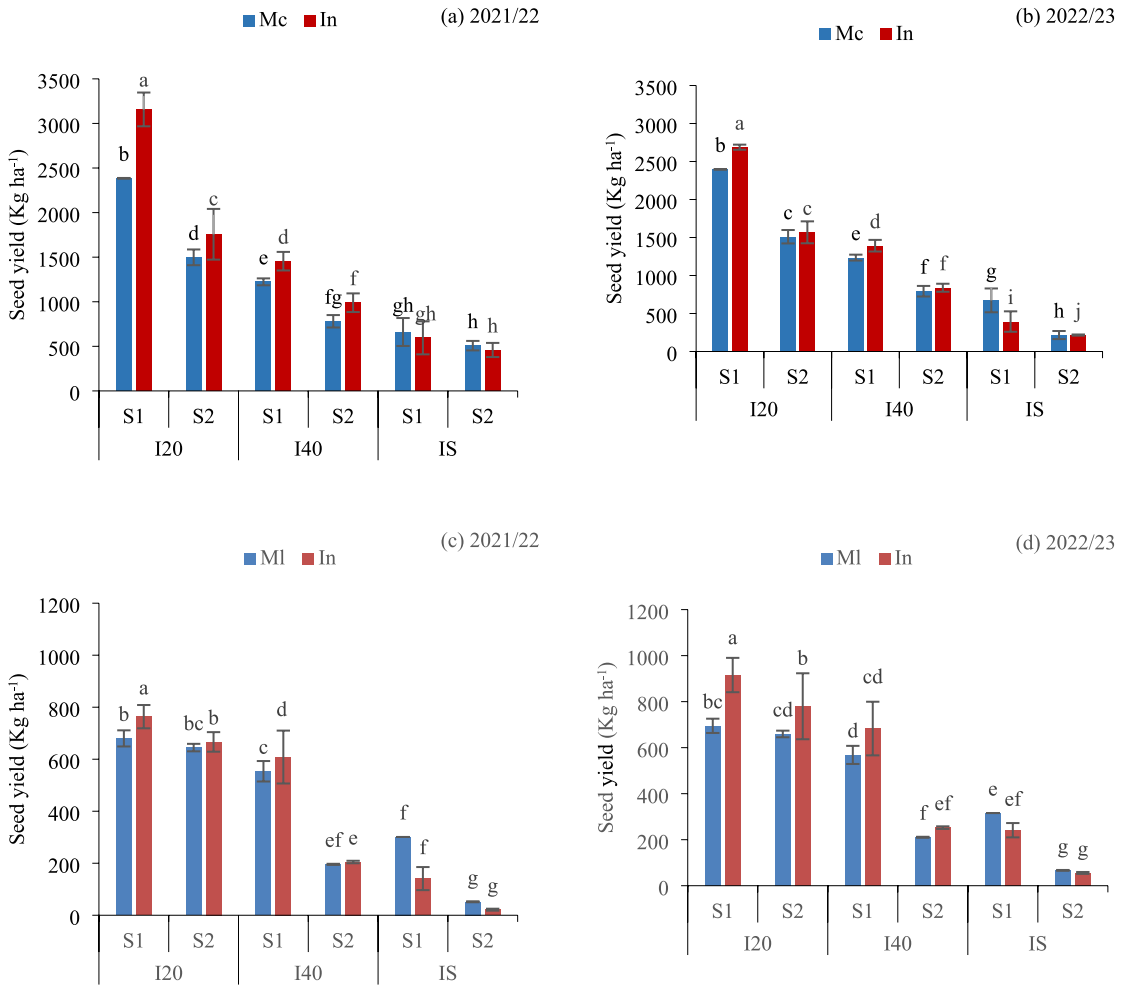

FIGURE 4 | Seed yield of chickpea (a, b) and *L. iberica* (c, d) under different cropping systems, sowing dates, and irrigation regimes during the 2021/22 and 2022/23 growing seasons at the experimental site. Mc: sole cropping of Chickpea; Ml: sole cropping of *L. iberica,* In: intercropping of 50% chickpea: 50% *L. iberica*; S1: autumn sowing date; S2: spring sowing date; I20: complete irrigation or control (irrigation based on 20% SAW); I40: Low irrigation (irrigation based on 40% SAW); IS: Supplementary irrigation (irrigation in two stages including the sowing and pre-flowering stage. Bars at each data point represent the standard deviation of the mean ($n = 3$). Different lowercase letters indicate a significant difference ($p \leq 0.05$) between treatments.

and autumn sowing dates resulted in a decrease in grain yield of 58.6% and 53.1%, respectively, compared to the Ml (IS) treatment (Figure 4c,d). This decrease was exacerbated by increased drought stress and higher temperatures during the spring sowing date compared to the autumn sowing date (Figure 4c,d).

3.4 | RUE of Chickpea and *L. iberica*

DM in the *L. iberica* and chickpea was linearly related to PAR in all intercropping treatments, and the correlation coefficient was greater than 0.9 in all cases. The slope of the linear relationship between the PAR and the DM was regarded as RUE. Concerning crop growth stages, RUE varies. The maximum RUE was observed for chickpea and *L. iberica* at 150 DAS (autumn sowing date) and 60 DAS (spring sowing date).

Chickpea in the In (I20) treatment had the highest average RUE (1.42 g/MJ) at the autumn sowing date. As compared to In (I20), there was a decrease of 7.6%, 17.14%, 4.9%, 45.76%, and 39.2% in the Mc (I20), Mc (I40), In (I40), Mc (IS), and In (IS) treatments, respectively (Figure 5a,b) Moreover, at the spring sowing date, it was lower by 13.3%, 0.69%, 18.6%, 14.9%, 45.7%, and 39.9% compared to the In (I20) treatment (Figure 5c,d).

The *L. iberica* with the In (I20) treatment had the highest average RUE (1.25 g/MJ) at the autumn sowing date. As compared to In (I20), there was a decrease of 14.64%, 22.08%, 19.56%, 33.52%, and 23.36% in the Mc (I20), Mc (I40), In (I40), Mc (IS), and In (IS) treatments (Figure 5e,f). Moreover, RUE at the spring sowing date was lower by 13.6%, 3.36%, 24.3%, 9.36%, 35.2%, and 23.76% compared to the In (I20) treatment (Figure 5g,h).

3.5 | Land Equivalent Ratio

Examining the average of 2 years, the In (I20) and In (I40) treatments had the highest LERt (2.43 and 2.30) of all the treatments under the autumn sowing date in both years. While the In (IS) treatment had the lowest LERt (1.28) under the spring sowing

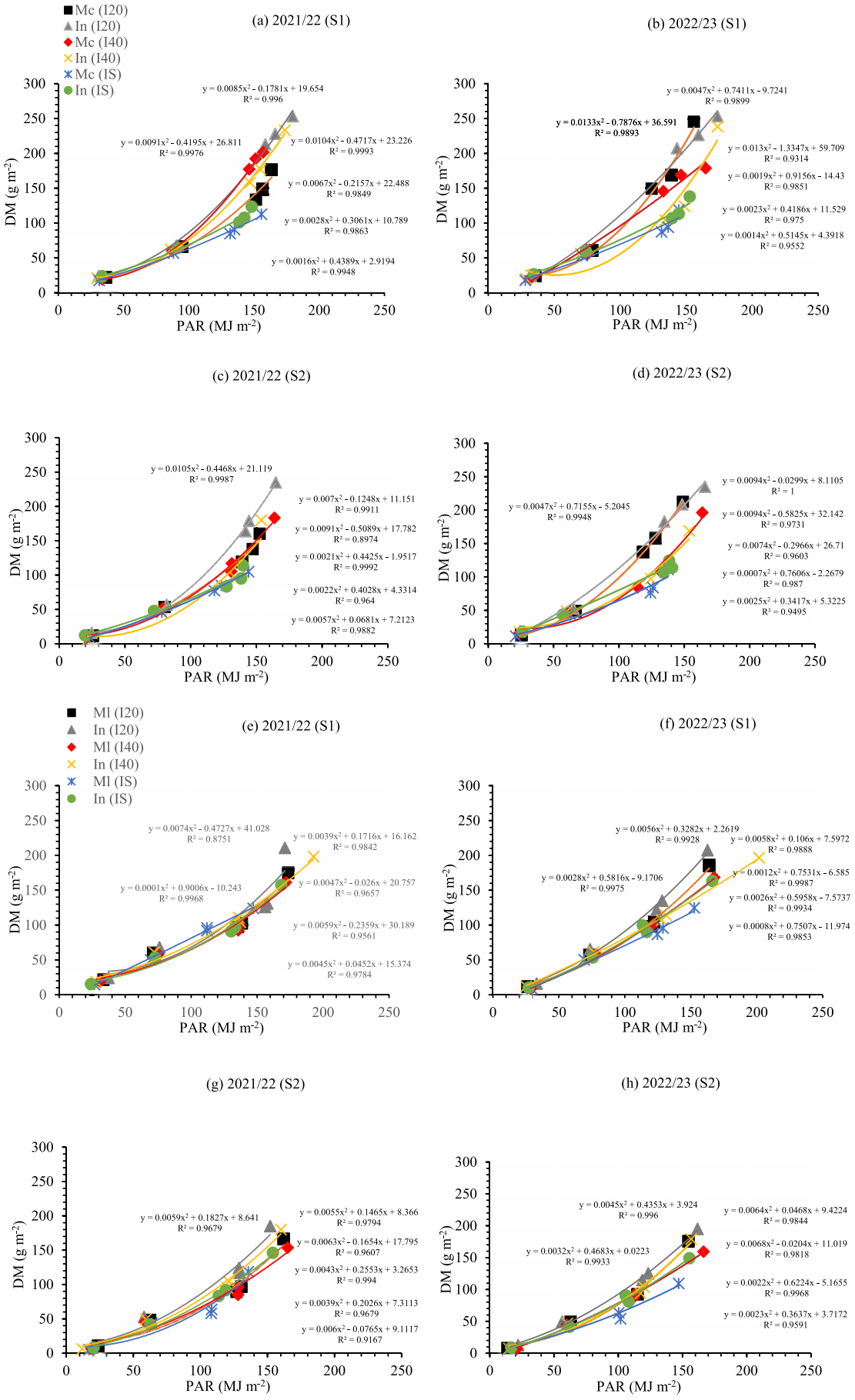

FIGURE 5 | Legend on next page.

FIGURE 5 | Radiation use efficiency (RUE) of chickpea (a–d) and *L. iberica* (e–h) under different cropping systems, sowing dates, and irrigation regimes during the 2021/22 and 2022/23 growing seasons at the experimental site. Mc: mono-cropping of chickpea; Ml: mono-cropping of *L. iberica*; In: intercropping of 50% chickpea: 50% *L. iberica*; S1: autumn sowing date; S2: spring sowing date; I20: complete irrigation or control (irrigation based on 20% SAW); I40: Low irrigation (irrigation based on 40% SAW); IS: Supplementary irrigation (irrigation in two stages including the sowing and pre-flowering stage) is based on 20% SAW.

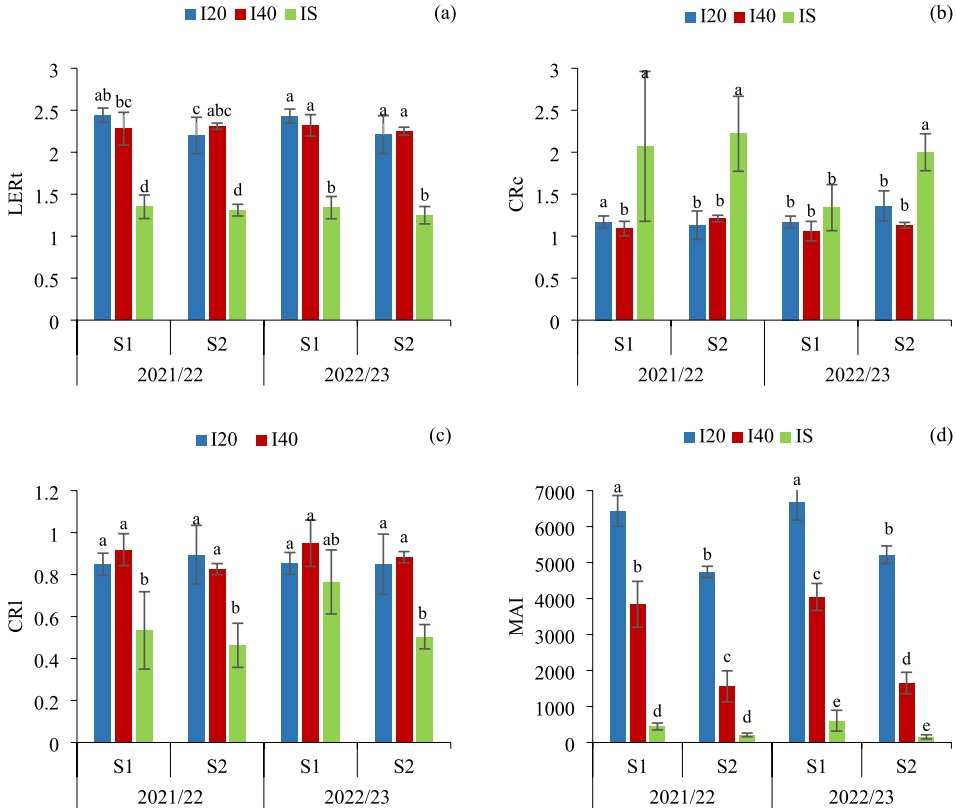

FIGURE 6 | Total land equivalent ratio (LERt, a), competitive ratio of chickpea (CRc, b) and *L. iberica* (CRl, c), and monetary advantage index (MAI, d) under different sowing dates and irrigation regimes during the 2021/22 and 2022/23 growing seasons in chickpea–*L. iberica* intercropping systems. In: intercropping of 50% chickpea: 50% *L. iberica*; S1: autumn sowing date; S2: spring sowing date; I20: complete irrigation or control (irrigation based on 20% SAW); I40: Low irrigation (irrigation based on 40% SAW); IS: Supplementary irrigation (irrigation in two stages including the sowing and pre-flowering stage). Bars at each data point represent the standard deviation of the mean ($n = 3$). Different lowercase letters indicate a significant difference ($p \leq 0.05$) between treatments.

date, in other words, to attain the same yield as the intercropping system of chickpea and *L. iberica* under I20 and I40 irrigation regimes, the monocropping system needs 143% (1.43 ha) and 130% (1.30 ha) more land area. This demonstrates the clear advantage of intercropping.

3.6 | Competitive Ratio Index

Over the study's 2 years, CRc values (Figure 6b) were higher than CRd values (Figure 6c) in every treatment. It demonstrates the chickpea plant's superiority over *L. iberica* in terms of better resource utilization in intercropping and the greater competitive power of this plant in absorbing some nutrients. In autumn and spring sowing conditions, the CRc of chickpea plants increased with increasing drought stress in the In (IS), In (I40), and In (I20) treatments, respectively. In addition, CRc increased more with increasing temperature and drought stress intensity (spring sowing date) than with autumn sowing date (Figure 6b). While CRd in the *L. iberica* plant decreased with increasing drought stress in the In (IS), In (I40), and In (I20) treatments, respectively (Figure 6c), there was a negative linear relationship between the CR of chickpea and *L. iberica* in the I20, I40, and IS irrigation regimes for both spring and autumn sowing dates. Due to the increase in drought stress intensity in IS irrigation regimes for both autumn and spring sowing dates, this issue is important in increasing chickpea resource efficiency.

3.7 | Monetary Advantage Index

The MAI values for chickpea and *L. iberica* were positive in all treatments. This demonstrates that intercropping systems are more economically viable than monocropping. However, at the autumn sowing date, MAI increased in In (I20) (6662) and In (I40) (3988) treatments, respectively. So, the MAI of In (I20) and In (I40) treatments was 97.61% and 96.1%, respectively, greater than In (IS) (Figure 6d).

4 | Discussion

4.1 | Leaf Area Index, Dry Matter, Competitive Ratio Index, and Seed Yield

The study highlights the advantages of intercropping chickpea and *L. iberica* over monocropping, demonstrating that mixed farming systems can offer significant benefits compared to pure farming. Compared to 2022/2023, the 2021/2022 season experienced more extreme temperature fluctuations and reduced rainfall, which posed greater environmental stress on crop growth. In 2022–2023, there was an increase in rainfall and a slight drop in temperature. Higher rainfall and lower temperatures seemed more favorable for chickpea and *L. iberica* growth in 2022/23. Despite climatic differences, the intercropping system maintained consistent seed yield, LAI, and dry matter across both years, indicating its resilience to environmental variability. Because climate changes such as temperature increase and rainfall decrease are more evident in 2021/22 compared to 2022/23, intercropping with increased production per unit area due to more use of resources such as light, water, and foodstuffs has maintained the stability of production in 2021/22. However, the seed yield and DM of intercropping treatments In (I20) and In (I40) increased each year. This indicated that the increased seed yield and DM of the intercropping system may reflect an improved chickpea yield that was independent of the intercropping or the facilitation between the chickpea and *L. iberica*. Most intercropping treatments showed sufficient LAI values to support efficient light interception, with only the In (IS) treatment falling below optimal thresholds. LAI values in intercropping treatments generally exceeded the minimum required for effective canopy function, reinforcing the structural advantage of mixed cropping systems. This overyielding in mixed plant communities, compared to sole cropping, can be attributed to resource use complementarity and facilitation between (Ammer 2019).

Complementarity in intercropping systems arises when niche partitioning reduces competition between species, enabling more efficient resource capture and higher overall productivity. Facilitation, on the other hand, occurs when one species benefits from the conditions created by another, such as improved nutrient availability or protection from environmental stressors (MacLaren et al. 2023). In this study, chickpea appeared to facilitate nutrient availability for *L. iberica*, leading to increased LAI and DM production. These interactions underscore the importance of functional diversity in minimizing competition and maximizing facilitation, which enhances the productivity of intercropping systems compared to monocropping (Zhang GuiGuo et al. 2011).

Diverging resource use strategies among plant species in intercropping systems can lead to overyielding, as some species are able to rapidly exploit readily available resources to minimize competition, while others may tolerate lower resource levels due to more efficient conservation mechanisms. However, facilitation introduces additional complexity, as less stress-tolerant species may benefit from the shelter provided by more robust partners, which can protect them from extreme weather conditions or insect pests (MacLaren et al. 2023).

Intercrop interactions are influenced by both aboveground and belowground processes, including competition for water and nutrients, as well as plant-microbe interactions (Engbersen et al. 2022). It is also possible that RUE, DM, LAI, and seed yield are linked to other traits that govern belowground interactions, further shaping the dynamics of intercropping systems.

In intercropping systems, the sowing date creates various degrees of asymmetric competition between species (Huang et al. 2018). Changing the sowing date to an earlier (autumn) sowing date significantly boosted the growth rate of chickpea and *L. iberica* during the growth period. As a result, differences in sowing time under intercropping can exacerbate the size disparity between plants planted earlier and later, which results in an unbalanced acquisition of resources such as light and water (Benjamin and Hardwick 1986). Because of this, intercropping systems decrease interspecific competition and boost resource uptake and yield through spatial ecological differentiation brought about by variations in water absorption depth between different products and temporal ecological differentiation brought about by different sowing dates (Zhang et al. 2023).

Thus, interspecific competitive behavior is crucial for maintaining the structural stability of the intercropping agroecosystem. Additionally, comprehending competitiveness can aid in predicting yields in an intercrop system (Wahla et al. 2009). The competitive ability of chickpea with *L. iberica* grew significantly in the In (IS) treatment relative to other treatments with increasing irrigation intervals and levels of drought stress. The greater CR of chickpea than *L. iberica* demonstrated the plant's superiority, aggressiveness, and capacity to use more resources. Due to the lower CR in all intercropping treatments under fall and spring sowing dates and the lower level of intraspecific competition in this study, *L. iberica* was considered a sub-crop. Therefore, this plant is appropriate for intercropping with chickpea on the autumn and spring sowing dates. This intercropping model is particularly beneficial for farmers in semi-arid regions of Iran such as East and West Azerbaijan, Kermanshah, and Lorestan, where water scarcity and soil degradation limit crop productivity (Ataei et al. 2023). The adaptability of *L. iberica* to drought and its low input requirements make it a suitable companion crop in dryland systems. Research has also demonstrated increased CR in low irrigation regimes compared to full irrigation regimes (Baghdadi et al. 2021). Generally, regardless of whether irrigation water was restricted or not, the CR index showed that chickpea dominated intercropping. For instance, previous studies have shown that adjusting sowing rates in intercropping systems can significantly enhance chickpea yield, highlighting the importance of crop arrangement and density. Increasing chickpea competitiveness over rapeseed likely contributed to the increase from 50 to 75 to 100 $kg\,ha^{-1}$ (Dowling et al. 2021).

4.2 | Radiation Use Efficiency

Under complete irrigation, the intercropping of chickpea and *L. iberica* demonstrated superior light interception compared to monocropping, primarily due to enhanced canopy structure and vertical leaf distribution (Raza, Feng, van der Werf, et al. 2019). The effects of chickpea facilitation seem to enhance nutrient availability in *L. iberica* plants, leading to increased LAI and DM production. Also, increased PAR transmission results in increased LAI, a measure of optimal leaf growth and expansion

that increases the ability of plant leaves to receive and use solar energy (Raza, Feng, van der Werf, et al. 2019). Therefore, intercropping under optimized irrigation regimes resulted in more efficient light utilization than monocropping, reflecting improved canopy dynamics and spatial resource use.

The main reason for the higher light consumption efficiency in the intercropping under IS regime is empty spaces in the monocropping system. These regions result in substantial light loss, diminishing the system's efficiency. Greater soil coverage in the intercropping system reduced radiation loss compared to monocropping, thereby enhancing overall light absorption. The inclusion of legume rows improved light penetration and distribution, which enhanced biomass conversion and contributed to increased RUE (Raza, Feng, Iqbal, et al. 2019b). The architecture of the canopy influences the radiation distribution among intercrop species. For example, a plant's leaf pattern can change how much light is intercepted and how much light is transferred to the soil (Ozier-Lafontaine et al. 1997).

On the other hand, increasing the intensity of drought stress in the In (IS) irrigation regime inhibits the effective net photosynthetic rate due to reducing PAR absorption, which gradually reduces RUE. Previous research has shown that drought stress during the wheat crop's reproductive stage has several effects on photosynthesis and significantly increases leaf senescence, which lowers the values of LAI and RUE (Luo et al. 2011). Another study found that water scarcity may also diminish the rate of photosynthesis, leading to a decrease in RUE (Torres et al. 2017).

Considering that, increasing canopy light absorption during the growing season is one of the effective factors in increasing photosynthesis and DM production. Light absorption, photosynthesis, and DM appear to have decreased due to the sowing delay brought on by high air temperatures during the plant growth period, an increase in phenological growth rate, and a shorter growth period (spring sowing date). However, it is also possible that high temperatures increase plant maintenance respiration because of the accelerated degradation of enzymes. This, in turn, may lead to a decrease in net photosynthesis's contribution to gross photosynthesis and a reduction in the total DM yield (Hammes and De Jager 1990).

Consequently, the rise in dry matter accumulation outpaced the increase in PAR, indicating improved light use efficiency under favorable intercropping conditions. This may be due to the optimal sowing pattern used in the intercropping system, which significantly improved the microclimate of chickpea and *L. iberica* and accelerated DM production in the intercropping species compared to other treatments.

4.3 | Land Equivalent Ratio, Monetary Advantage Index

In this study, all intercropping treatments demonstrated LER values above the threshold for productivity advantage, confirming the ecological and agronomic benefits of mixed cropping over monocrops. This reinforces the notion that intercropping enhances resource use efficiency and overall system productivity compared to monocropping. The higher productivity of the intercrop system compared to the monocrops may have resulted from the complementary and efficient use of resources by the component crops (Kamara et al. 2017). In intercropping, the legume components usually have a greater competitive ability due to their relatively high growth rate, height advantage, and larger root system. Accordingly, Ghosh et al. (2006) reported that higher LER values were associated with economic benefits as expressed by MAI values.

An economic advantage of intercropping can be demonstrated using the MAI (Zhu et al. 2023). Positive MAI values across treatments reflect the economic viability of intercropping chickpea with *L. iberica*, especially under complete irrigation and autumn sowing conditions. This demonstrates that intercropping systems are more economically viable than monocropping. Drought stress and extended irrigation intervals reduce economic returns and yield stability, highlighting the sensitivity of intercropping systems to water availability. These outcomes align with those Amira reported (El-Mehy et al. 2020). Therefore, the intercropping of chickpea and *L. iberica* under irrigation regimes I20 and I40, with an autumn sowing date, is economically viable in the study area. Beyond agronomic performance, *L. iberica* contributes added value through its oil-rich seeds, which contain up to 38% alpha-linolenic acid. This oil is used in pharmaceuticals, cosmetics, and as a substitute for linseed oil in industrial applications such as varnish, ink, and soap (Naghibi et al. 2005; EuPIA 2014). These properties make it a strategic crop for diversifying farm outputs and increasing profitability in low-input systems.

5 | Conclusion

One of the most significant challenges impeding agricultural product production is the diminishing productivity of environmental resources. The most efficient strategy to promote resource efficiency is to use appropriate crop systems and determine the optimal crop sowing pattern, depending on each region's ecological characteristics. After evaluating the intercropping and monocropping systems of chickpea and *L. iberica* under irrigation regimes and sowing date, the findings showed that the In (I20) treatment is beneficial in increasing yield, RUE, and land use efficiency compared to other treatments under the autumn sowing date. These results indicate that intercropping chickpea and *L. iberica* increases resource use efficiency. Chickpea's higher competitiveness and yield chickpea lead to improved resource use in intercropping compared to *L. iberica*. It allows interspecific facilitation to be fully provided, which thus increases land use efficiency and economic benefits. Our study's overall findings emphasize the significance of the intercropping systems of *L. iberica* and chickpea in facilitating interspecies interactions that can enhance agricultural productivity and sustainability. Based on the findings, it can be concluded that the In (I20) treatment, followed by the In (I40) treatment, was introduced as the most effective treatment during the autumn sowing date regarding resource use efficiency. Overall, the study underscores the potential of intercropping to enhance agricultural productivity and resource use efficiency, making it a more favorable approach compared to pure monocrop farming. Therefore, more studies are needed to gain in-depth knowledge

about the different proportions of chickpea and *L. iberica* cultivation and to choose the best ratio of chickpea and *L. iberica* intercropping to increase the productivity of resources.

Author Contributions

The concept research was designed by M.M., S.M.F., and A.R., with M.M. conducting the experiment. The manuscript has been approved and agreed upon by all authors. The authors have stated that they do not have any conflicts of interest.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **TABLE S1:** Variance analysis of the effect of year, irrigation regime (I20, I40, IS), sowing date (S1, S2), and cultivation system (Mc, Ml, In) on plant growth parameters and yield of *L. iberica* in 2021 and 2022. **TABLE S2:** Variance analysis of the effect of year, irrigation regime (I20, I40, IS), sowing date (S1, S2), and cultivation system (Mc, Ml, In) on plant growth parameters and yield of *L. iberica* in 2022 and 2023. **TABLE S3:** The combined analysis of variance for the effect of year, irrigation regime (I20, I40, IS), sowing date (S1, S2), and cultivation system (Mc, Ml, In) on plant growth parameters, and yield of *L. iberica* in 2021–22 and 2022–23. **TABLE S4:** Variance analysis of the effect of year, irrigation regime (I20, I40, IS), sowing date (S1, S2), and cultivation system (Mc, Ml, In) on plant growth parameters and yield of Chickpea in 2021 and 2022. **TABLE S5:** Variance analysis of the effect of year, irrigation regime (I20, I40, IS), sowing date (S1, S2), and cultivation system (Mc, Ml, In) on plant growth parameters and yield of Chickpea in 2022 and 2023. **TABLE S6:** The combined analysis of variance for effect of year, irrigation regime (I20, I40, IS), sowing date (S1, S2), and cultivation system (Mc, Ml, In) on plant growth parameters, and yield of Chickpea in 2021–22 and 2022–23.