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ORIGINAL ARTICLE

Assessment of some herbicide effects on the weed control and agronomic traits of *Camelina sativa* under irrigation and rainfed conditions

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Abstract

Climatic fluctuations in semi-arid areas are modifying the dynamics of weeds in field crops production. This trial was aimed to research the application of various herbicides on the growth characteristics of camelina under irrigation and rainfed conditions in Maragheh, Iran. Analyzing the data via treatment by a trait biplot model based on principal component (PCA) indicated that the PCA1 and PCA2 explained 74 and 17% of the observed variability, "respectively". Most traits were grouped under the I1-H3 (irrigated + cycloxydim) section while the number of siliques per plant was positioned with I1-H5 (irrigated + pinoxaden), and I1-H1 (irrigated + without herbicide) produced a high harvest index as well as density and biomass of weeds. The seed yield, biological yield, thousand-seed weight, seed number per silique, canopy diameter, chlorophyll content, plant height, and the number of siliques per plant were correlated similar to association of weed density with biomass. Herbicides H3, H4 (haloxyfop-R-methyl), and H5 were positively correlated under irrigated conditions, while H2 (trifluralin), H3, H4, and H5 were positively associated under rainfed circumstances. The number of siliques per plant, seeds per silique, and seed yield demonstrated high discriminative ability as well as greater typical ability. Treatments H2, H4 and H5 under irrigation conditions were identified as ideal or distinguishing treatments. The response of treatments for seed yield indicated that H3, H4 and H5 under full-irrigated conditions were the most effective in terms of yield performance. Overall, this study underscored that the availability of water strongly affected the effectiveness of herbicides, thus, it seems necessary to use climate smart agricultural practices in drought prone regions such as supplemental irrigation to improve the effectiveness of acetyl CoA carboxylase inhibitor herbicides.

Keywords: cycloxydim, haloxyfop-R-methyl, herbicide efficacy, pinoxaden, treatment by trait interaction

Introduction

Water scarcity is a key challenge for crop productivity in semi-arid regions, worsened by climate change and rising temperatures. *Camelina sativa*, a resilient oilseed crop from the Brassicaceae family, has regained interest due to its ability to produce reasonable yields with minimal inputs (Sydor *et al.* 2022). It is highly resistant to pests, diseases, drought, heat, and salinity. However, weed competition remains a major issue, impacting net productivity. Traditional crop breeding has prioritized yield over stress tolerance, making effective weed management crucial (Cierjacks *et al.* 2016). While camelina cultivation is increasing in semi-arid regions, research on herbicide efficacy in its production remains limited, highlighting the need for studies on optimizing weed control strategies to enhance yield potential.

Semi-arid climates present significant challenges to plant growth, including limited and irregular rainfall, low winter temperatures at higher altitudes, nutrient deficiencies, high soil pH, and prolonged dry spells

(Fattahi *et al.* 2023; Janmohammadi *et al.* 2024). Most precipitation occurs during the cold months when plants are in the inactive rosette stage, further restricting growth. While some studies have examined the effects of water scarcity on camelina, showing declines in vegetative growth, seed yield, and oil quality, little research has explored how drought affects herbicide efficacy in camelina cultivation. Pre-plant herbicides, like quinclorac and pendimethalin, have been tested, revealing that camelina's early growth stage is highly sensitive to these soil-applied herbicides. However, as the plant matures, the negative effects diminish, with quinclorac proving to be the safest option (Jha and Stougaard 2013). Further research is needed to optimize herbicide use under water-limited conditions to support camelina production in semi-arid regions.

Propaquizafop and quizalofop-p-ethyl are systemic herbicides absorbed through both foliage and roots, transported via the phloem, and act by inhibiting fatty acid synthesis through acetyl-CoA carboxylase (ACCase) (Jursík *et al.* 2021). Testing these herbicides on different camelina varieties revealed varying effects on chlorophyll fluorescence and photosystem II function (Sobiech *et al.* 2020). In contrast, clopyralid and picloram, selective herbicides targeting broadleaf weeds and woody plants by mimicking auxin, had minimal influence on camelina's photosynthetic performance (Sobiech *et al.* 2020). Under water-deficit conditions, herbicides such as clodinafop-propargyl and mesosulfuron-methyl + iodosulfuron-methyl sodium showed significantly reduced effectiveness (Alizade *et al.* 2021), likely due to decreased stomatal conductance limiting herbicide absorption. While some studies have examined specific herbicides in camelina cultivation, their performance under different moisture conditions remains largely unexplored, highlighting the need for further research. Due to the dominance of cereal cultivation in the semi-arid regions of northwestern Iran, many narrow-leaved weeds are prevalent in these areas. With the introduction of camelina to these areas, there is a need to evaluate common herbicides, especially ACCase inhibitors types in production systems. This study aimed to assess the effects of trifluralin and the post-emergence herbicides cycloxydim, haloxyfop-R-methyl, and pinoxaden on weed control and camelina seed yield components under well-irrigated and rainfed conditions.

Materials and Methods

Trial

A field trial was conducted in Maragheh, Iran (37°23'N,46°16'E) during the 2023–2024 cropping season. This region receives most of its precipitation in winter, with a total of 294 mm recorded from September to July, approximately 70% of which falls as snowfall. The field's soil is silty loam with a pH of 7.8 and key properties including low organic matter (0.3%), nitrogen (0.1%), calcium carbonate (11%), electrical conductivity (0.92 dS · m^{-1}), phosphorus (11.3 mg · kg^{-1}), and potassium (282 mg · kg^{-1}). The field remained fallow the previous season. In autumn, primary tillage was performed using a moldboard plow, incorporating 10 tons per hectare of farmyard manure. In early March, secondary tillage followed with a disc harrow, rotavator, and leveler. The soil was then shaped into ridges and furrows using a Hiller-Furrower, with ridges spaced 50 cm apart, 10 cm wide at the top, and 15 cm high. Before planting, phosphorus (60 kg as triple superphosphate) and nitrogen (100 kg as urea) were applied per recommended rates. In mid-March, the field was divided into main and sub-plots for experimentation. Camelina seeds (Sohail cultivar) were obtained from the Dryland Agricultural Research Institute, Iran. This variety is highly adaptable to diverse climates and soils, demonstrating superior drought tolerance compared to other oilseed crops (Kahrizi *et al.* 2018). It requires less water, fertilizer, and pesticides while exhibiting strong cold resistance. The seeds were manually planted on ridge tops at a depth of 1.5 cm, with 5 cm spacing between rows. Sowing coincided with the start of the rainy season, allowing natural rainfall to support germination and seedling establishment.

Treatments

The experiment followed a split-plot design (2 × 5) within a randomized complete block framework, with three replications. The main factor included two irrigation regimes: I1 (irrigated) and I2 (rainfed). In the irrigated treatment, the field received eight irrigation events from planting to harvest, totaling 550 mm of water. Sub-plots were assigned to five herbicide treatments including H1, no herbicide application (control); H2, trifluralin (pre-emergence); H3, cycloxydim (post-emergence); H4, haloxyfop-R-methyl (post-emergence); and H5, pinoxaden (post-emergence). Trifluralin (Treflan, CAS 1582-09-8) was applied at 1.5 l · ha^{-1} 10 days before planting, following plowing and disc operations, and was incorporated into the soil using a light disc. This herbicide inhibits microtubule synthesis, disrupting mitosis and preventing weed seedling germination and growth. Cycloxydim is a systemic, selective herbicide from the cyclohexane oxime group, specifically targeting narrow-leaved weeds in canola crops. It is applied at 2 l · ha^{-1} post-emergence, once narrow-leaved weeds reach the four- to five-leaf stage.

Haloxyfop-R-methyl (Galant Super, EC 10%, produced by Mehr Parsian Exir Co., Iran) is a systemic, selective herbicide effective against a wide range of annual and perennial narrow-leaved weeds. It is applied at a rate of 1 l per hectare when the weeds are at the two- to five-leaf stage. Belonging to the aryloxyphenoxypropionate group, haloxyfop-R-methyl is absorbed by plants within 1 hour of application. Pinoxaden (Axial, EC 5%, produced by Aria Shimi, Iran) is the only herbicide available in the pinoxaden group, targeting and inhibiting the growth of narrow-leafed grasses. It was applied when the weeds had four to six leaves, at a rate of 1.2 l per hectare. In the control treatment, no herbicide was applied, and the weeds were sprayed with distilled water. All herbicides were applied following the recommended protocols during the weeds' vegetative stage using a motorized backpack sprayer (Solo model 433). Post-emergence herbicides were applied to the above-ground parts of the weeds early in the day, ensuring complete coverage of the weed shoots without runoff.

Traits

Following the application of post-emergence herbicides and at the midpoint of the main stem elongation phase, surviving weeds between and within the rows were counted using a 1 m^2 quadrat in each experimental plot. Weed population density was recorded as the number of weeds per square meter. The weeds were then cut above the ground, treated at 70°C for 48 hours in an oven to determine weed dry biomass. At the early flowering stage, chlorophyll content in the upper, fully developed leaves of camelina was measured using a SPAD 502 chlorophyll meter (Konica Minolta, USA). At physiological maturity, plant height was measured from a 1 m^2 quadrat randomly taken from each plot, and canopy diameter was assessed by measuring from left to right to evaluate lateral canopy growth. After harvesting and drying the camelina plants, seed yield components were calculated, including the number of siliques per plant, seeds per silique, 1000-seed weight, yield per unit area, biological yield, and the harvest index.

Biplot analysis

The entry-by-tester biplot model, implemented through the GGEbiplot application (Yan 2024), is a powerful tool for analyzing datasets, including those derived from various herbicide and irrigation treatments. This model is based on principal component analysis (PCA) and facilitates the visualization and interpretation of interactions between entries (e.g., treatments) and testers (e.g., traits) using the following equation:

$$\frac{Y_{ij}-\bar{Y}_J}{\sqrt{S_j^2}} = \sum_{n=1}^{2} \Phi_n \Psi_{in} \Omega_{jn} + R_{ij},$$

where:

Y_{ij} is the average of treatment i for trait;

$\bar{Y}_J$ is the means Y_{ij}; S^2_j is the variance;

Φ_n is the eigen-value for PCA n;

Ψ_{in} is score of entry i on PCA n;

Ω_{jn} is score of tester j on PCA n;

R_{ij} is the unaccounted variability of the computed equation.

To obtain symmetrical scores for both treatments and traits, ensuring their comparability, the Φ value is transformed through vector absorption, leading to a more precise representation of treatments and traits. The entry-by-tester interaction biplots are generated using score scales, where each entry or tester is represented as a distinct point on the plot. By applying this model, valuable insights are gained into the effects of herbicides and irrigation on camelina, providing a foundation for optimizing future agricultural practices.

Results and Discussion

Model fitting

The first and second principal components (PCs) collectively explained 91% of the total variability (Fig. 1), with the first PC accounting for 74% and the second PC for 17%. This variation in the entry-by-tester interaction underscores the substantial influence of both additive and crossover effects, which contribute to shifts in treatment rankings across traits. These findings align with those of Sabaghnia and Janmohammadi (2016) in sunflower, who emphasized the challenges of selecting optimal treatments without considering entry-by-tester interactions. Therefore, the application of the biplot method is strongly recommended to effectively address these complexities. Similarly, Yari *et al.* (2018) demonstrated that the entry-by-tester biplot model serves as a robust analytical tool for examining the relationships between treatments and traits.

Polygon-view

Figure 1 provides a visual representation of the impact of herbicide and irrigation treatments, identifying treatment combinations that were most effective for specific traits. Several agronomic traits, including seed yield (SY), biological yield (BY), thousand-seed weight (TSW), seed number per silique (SNS), canopy diameter (CD), chlorophyll content (CC), and plant height (PH), were clustered under the I1-H3 treatment (irrigation + cycloxydim). Our results indicated that cycloxydim, when applied under optimal soil moisture conditions, exerted a more pronounced positive effect on both vegetative and reproductive growth in

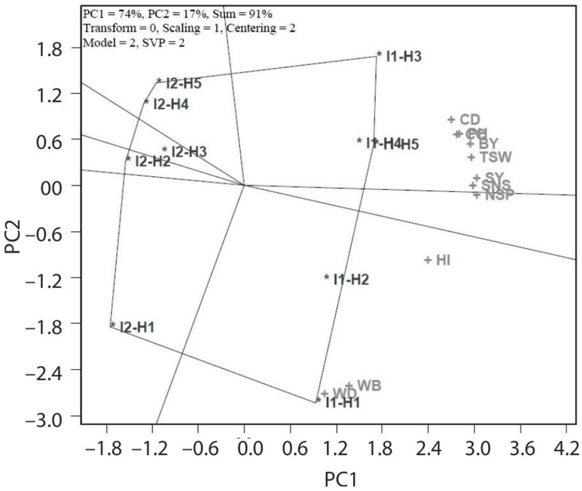

Fig. 1. A heptagon of a biplot model showing the reaction of camelina traits under various treatments. Treatments are: I1 – irrigated conditions; I2 – rainfed circumstances; H1 – no application of herbicide; H2 – trifluralin; H3 – cycloxydim; H4 – haloxyfop-R-methyl; and H5 – pinoxaden. Traits are: WD – weed density; WB – weed biomass; HI – harvest index; SY – seed yield; BY – biological yield; TSW – thousand-seed weight; SNS – seed number per silique; NSP – number of siliques per plant; CD – canopy diameter; CC – chlorophyll content; and PH – plant height

camelina. As a selective herbicide targeting grasses, cycloxydim is less detrimental to crops than the broad-spectrum herbicide trifluralin, even when applied during active growth. Moreover, the findings suggest that irrigation plays a critical role in herbicide efficacy. Under drought conditions, reduced herbicide mobility within vascular systems, lower absorption rates, and altered herbicide metabolism in weeds, resulting from oxidative stress, can significantly impair herbicidal effectiveness (Alizade *et al.* 2020).

The number of siliques per plant (NSP) was positioned separately, with the I1-H5 treatment (irrigated + pinoxaden) being the most effective for this trait. The superior performance of pinoxaden compared to other herbicides under irrigation conditions in improving camelina growth can be attributed to its ability to eliminate weeds during reproductive stages, thereby reducing competition between weeds and camelina. The lack of effectiveness of pinoxaden under rainfed conditions is likely due to physiological and anatomical adaptations in weeds, including xenobiotic compartmentalization and detoxification mechanisms such as hydroxylation or dealkylation mediated by cytochrome P450 (Kulasekaran *et al.* 2017; Yanniccari *et al.* 2020). Furthermore, the I1-H1 treatment (irrigated + no herbicide) was associated with high values for weed density (WD), weed biomass (WB), and harvest index (HI). In contrast, the four remaining vertex treatments, I2-H1, I2-H2, I2-H3, and I2-H4 (rainfed + no herbicide, trifluralin, haloxyfop-R-methyl, and pinoxaden, respectively), performed poorly across all measured traits. These findings suggest that camelina yield is primarily influenced by soil moisture availability, and that weed control under rainfed conditions is less effective than under irrigation. Among the herbicide treatments, cycloxydim (H3) produced the highest yield and yield components, demonstrating greater efficacy than the other applied herbicides. The fitted entry-by-tester biplot model effectively highlighted variations in camelina traits under different irrigation and herbicide treatments, facilitating the identification of the most optimal treatment combination. Therefore, for camelina cultivation in semi-arid regions, farmers should consider appropriate irrigation practices and weed control strategies, particularly using cycloxydim, to achieve optimal results. One potential factor that could reduce the effectiveness of cycloxydim is photolysis on leaf surfaces. Previous studies indicate that increased accumulation of waxes on leaf cuticles accelerates the photolysis rate of this herbicide (Xi *et al.* 2022). However, under favorable humidity conditions, reduced wax deposition on the cuticle appears to enhance herbicide penetration and efficacy in weed control (Monadjemi *et al.* 2014).

This experiment revealed that irrigation conditions played a significant role in determining the effectiveness of herbicides in camelina cultivation, with irrigated treatments generally showing better results in terms of weed control and crop yield. Irrigated conditions (I1) supported better herbicide absorption and activity because the higher soil moisture facilitated the movement of herbicides within the soil and plants. This meant that when camelina was irrigated, herbicides like cycloxydim (H3) worked more effectively, controlling weeds and allowing the crop to thrive. Under these conditions, cycloxydim resulted in enhanced vegetative and reproductive growth, contributing to better traits like seed yield, biological yield, thousand-seed weight, canopy diameter, and chlorophyll content. Cycloxydim is a selective herbicide for grasses, and its systemic action works better under moist conditions, as it can be absorbed more efficiently by both the foliage and the roots. In contrast, under rainfed conditions (I2), where water availability was limited, herbicides showed reduced effectiveness. This was particularly true for trifluralin (H2), haloxyfop-R-methyl (H4), and pinoxaden (H5), where the lack of moisture likely hindered their movement in the plants' vascular systems. Decreased absorption of these herbicides under dry conditions meant that they could not work as efficiently to control weeds. Furthermore, drought-induced oxidative stress could alter how weeds metabolize herbicides, possibly leading to detoxification and reduced herbicide efficacy.

Cycloxydim (H3), applied post-emergence, was the most effective herbicide under irrigated conditions. It was particularly beneficial for controlling grasses and promoting camelina growth by reducing weed competition. Cycloxydim does not damage camelina crops, even if applied slightly over the recommended dose during active growth, making it a safer choice for camelina cultivation. Pinoxaden (H5), also a post-emergence herbicide, was most effective for controlling weeds under irrigated conditions. This herbicide was particularly beneficial for the number of number of siliques per plant (NSP), which suggests its positive impact during the reproductive stages of camelina. Pinoxaden works by inhibiting ACCase in grass weeds, but its effectiveness was diminished under rainfed conditions. The lower efficacy of pinoxaden under rainfed conditions could be linked to physiological changes in the weeds, such as detoxification mechanisms (e.g., cytochrome P450-mediated detoxification), which might reduce herbicide uptake and effectiveness in stressed, drought-affected weeds. Trifluralin (H2) and haloxyfop-R-methyl (H4), both pre- and post-emergence herbicides, showed reduced efficacy under rainfed conditions compared to irrigated ones. Trifluralin, which inhibits microtubule formation in weeds, was particularly ineffective when water was scarce, as it relies on soil incorporation and effective root absorption. Similarly, haloxyfop-R-methyl, an herbicide targeting broadleaf weeds and some grasses, worked better under irrigated conditions, where its absorption and translocation through plants were more efficient. Under rainfed conditions, these herbicides had limited success due to lower herbicide movement and reduced absorption in dry soils.

The efficacy of herbicides under irrigated conditions was largely determined by their systemic nature and how well they were absorbed and transported within the plant system. Cycloxydim and pinoxaden both showed high efficacy in reducing weed density and promoting camelina growth, as they could move efficiently through the plant under favorable moisture conditions. In contrast, broad-spectrum herbicides like trifluralin did not perform as well under both irrigated and rainfed conditions, as they tend to affect a wide range of weeds and have a more severe impact on soil health and crop safety, potentially hindering camelina growth. Weed competition was notably reduced under irrigated conditions, which might explain the improved number of siliques per plant and other yield components in treatments where cycloxydim and pinoxaden were used. These herbicides helped control weeds during the crucial reproductive phase, reducing competition and allowing camelina to allocate more resources to seed development. However, under rainfed conditions, where weeds are harder to control due to limited herbicide efficacy, weed competition became a major limiting factor for camelina growth and seed yield.

Traits' associations

The correlation among testers, as illustrated in Figure 2A, depicts the relationships between the measured traits of camelina. The cosine of the angles formed by the trait vectors relative to the origin indicates the strength and direction of these relationships. Traits are positively correlated when their vectors form an angle smaller than 90°, negatively correlated when the angle exceeds 90°, and unrelated when the angle is exactly 90°. In Fig. 2A, weed density (WD) and weed biomass (WB) exhibit a strong positive correlation, as indicated by their small acute angles. Similarly, other agronomic traits, including seed yield (SY), biological yield (BY), thousand-seed weight (TSW), seed number per silique (SNS), canopy diameter (CD), chlorophyll content (CC), plant height (PH), and the number

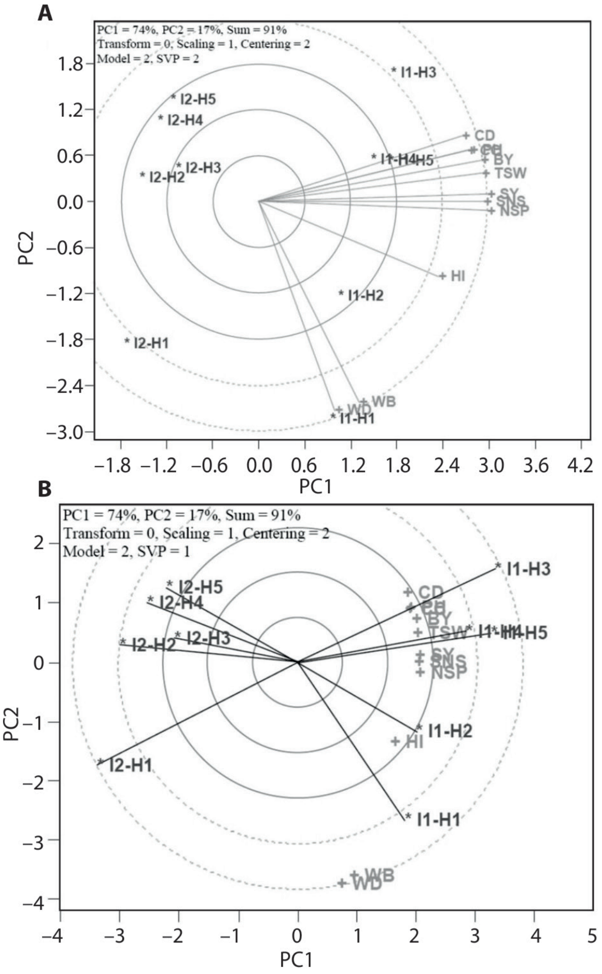

Fig. 2. Vector-option of biplot model showing relations between A – traits and B – treatments in camelina. Treatments are: I1 – irrigated conditions; I2 – rainfed circumstances; H1 – no application of herbicide; H2 – trifluralin; H3 – cycloxydim; H4 – haloxyfop-R-methyl; and H5 – pinoxaden. Traits are: WD – weed density; WB – weed biomass; HI – harvest index; SY – seed yield; BY – biological yield; TSW – thousand-seed weight; SNS – seed number per silique; NSP – number of siliques per plant; CD – canopy diameter; CC – chlorophyll content; and PH – plant height

of siliques per plant (NSP), also show positive correlations, as reflected by their acute angles. In contrast, the correlations between weed density (WD) and weed biomass (WB) with all other agronomic traits, except for harvest index (HI), were close to zero, as indicated by the approximately 90° angles. The entry-by-tester interaction biplot model's predictions regarding trait relationships closely align with the numerical correlations presented in Table 1. However, minor discrepancies may exist due to the model explaining 91% of the variation rather than a complete 100%. Previous research by Fallah *et al.* (2023) also demonstrated that camelina yield performance is strongly associated with biomass, thousand-seed weight, seed number per silique, plant height, and the number of siliques per plant. The analysis of trait correlations in Figure 2A reinforced the fact that camelina's productivity is influenced by multiple interrelated factors, with weed control playing a crucial role, especially under irrigated conditions. Managing these correlated traits, particularly by controlling weeds through effective herbicide use, can significantly improve camelina's growth and yield.

Treatments' associations

Similarly, the correlation among entries, as illustrated in Figure 2B, highlights the associations between treatments. Under irrigated conditions, I1-H3, I1-H4, and I1-H5 exhibited a positive correlation, as indicated by their small acute angles. These findings confirm that under full irrigation, aryloxyphenoxypropionate herbicides demonstrated comparable efficacy in reducing competitive pressure from narrow-leaved weeds. The probable mechanism behind this effect was the suppression of weed competition, which enhances camelina growth by improving photoassimilate production, increasing soil nutrient availability, optimizing soil moisture conditions in the rooting zone, and enhancing light absorption by the crop canopy. Ghidoli *et al.* (2023) reported that with optimal agricultural management and improved establishment of *C. sativa* under favorable moisture conditions, the plant can effectively compete with weeds by expanding its canopy and covering the soil surface.

The treatments under rainfed conditions (I2-H2, I2-H3, I2-H4, and I2-H5) also exhibited positive correlations, as indicated by their acute angles. Conversely, I1-H3 demonstrated a negative relationship with I2-H1, while I1-H2 showed a negative association with I2-H4 and I2-H5, as reflected by their obtuse angles (Fig. 2B). Similarly, I2-H2 was negatively correlated with I1-H4 and I1-H5, as indicated by their obtuse angles. These results highlight a significant distinction between irrigated and rainfed treatments, although the performance of H4 (haloxyfop-R-methyl) and H5 (pinoxaden) remained consistent across both conditions. Under irrigation, notable differences were observed between H2 (trifluralin) and H3 (cycloxydim) compared to H4 and H5. However, under rainfed conditions, these differences diminished, and all treatments, except for the control, exhibited relatively similar responses. It is important to note that the continuous use of ACCase-inhibiting herbicides has led to an increasing occurrence of resistance in certain narrow-leaved weed species, including *Avena sterilis*, *Avena fatua*, *Phalaris minor*, *Phalaris paradoxa*, and *Lolium rigidum*, particularly in northwestern Iran (Gherekhloo *et al.* 2016). Under rainfed conditions, herbicides H4 (haloxyfop-R-methyl) and H5 (pinoxaden) were effective across all treatments, showing consistent performance in weed control and agronomic traits. Under irrigated conditions, cycloxydim and trifluralin performed better than the rainfed, with cycloxydim showing a positive correlation with several growth traits. Herbicide efficacy is strongly influenced

Table 1. Associations among traits of camelina under various herbicides and water regimes

	WD	WB	PH	CH	CD	NSI	SNS	TSW	BYC	SYC
WB	0.920									
PH	0.138	0.212								
CH	0.063	0.205	0.803							
CD	0.068	0.136	0.852	0.795						
NSI	0.365	0.482	0.932	0.871	0.848					
SNS	0.314	0.421	0.905	0.874	0.845	0.977				
TSW	0.205	0.325	0.950	0.916	0.840	0.967	0.928			
BYC	0.190	0.281	0.942	0.892	0.941	0.954	0.934	0.946		
SYC	0.290	0.398	0.886	0.919	0.900	0.973	0.967	0.954	0.956	
HIC	0.469	0.564	0.530	0.694	0.564	0.747	0.765	0.702	0.601	0.808

Significant levels are 0.63 and 0.77 at 0.05 and 0.01 statistical level in DF = 8. Traits are: WD – weed density; WB – weed biomass; HI – harvest index; SY – seed yield; BY – biological yield; TSW – thousand seed weight; SNS – seed number per silique; NSP – number of siliques per plant; CD – canopy diameter; CC – chlorophyll content; and PH – plant height by irrigation, with cycloxydim and trifluralin showing reduced effectiveness under rainfed conditions. Haloxyfop-R-methyl and pinoxaden showed similar positive effects under both conditions, suggesting that they are reliable choices for both rainfed and irrigated camelina cultivation. The issue of herbicide resistance in certain weed species emphasizes the need for effective management strategies to ensure sustainable weed control and maintain the efficacy of herbicides.

Ideal trait

The discriminative ability of a trait is reflected in its standard deviation, with a higher ability indicated by a closer proximity to the ideal trait position (Fig. 3A). Traits closer to this ideal position are considered more favorable, while those positioned farther from it are less effective. In this study, traits such as the number of siliques per plant (NSP), seed number per silique (SNS), and seed yield (SY) demonstrated high discriminative ability. These were followed by harvest index (HI), biological yield (BY), thousand-seed weight (TSW), chlorophyll content (CC), and plant height (PH). All traits exhibited discriminative ability above the mean level, enabling them to effectively differentiate between the treatments (Fig. 3A). The typical ability of a trait, which reflects how well it represents the characteristic, is determined by the angle between the trait's vector and the horizontal axis (which represents the average of all traits). A smaller angle indicates greater typical ability. Consequently, the more favorable traits; NSP, SNS, and SY, had smaller angles with the horizontal axis, indicating higher typical ability. In contrast, canopy diameter had a larger angle, reflecting relatively lower typical ability (Fig. 3A).

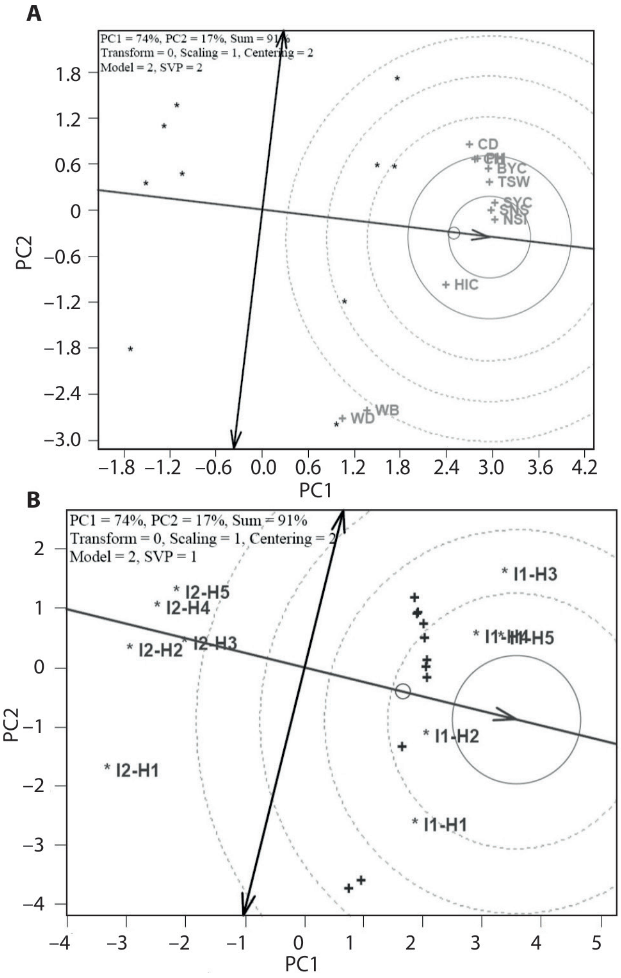

Fig. 3. A – perfect trait and B – perfect treatment tool of biplot model showing the position of the perfect trait and treatment in camelina. Treatments are: I1 – irrigated conditions; I2 – rainfed circumstances; H1 – no application of herbicide; H2 – trifluralin; H3 – cycloxydim; H4 – haloxyfop-R-methyl; and H5 – pinoxaden. Traits are: WD – weed density; WB – weed biomass; HI – harvest index; SY – seed yield; BY – biological yield; TSW – thousand-seed weight; SNS – seed number per silique; NSP – number of siliques per plant; CD – canopy diameter; CC – chlorophyll content; and PH – plant height

Ideal treatment

The potential for distinguishing treatments based on traits and their typical ability to highlight key characteristics is represented by an idealized treatment, known as the perfect position (Fig. 3B). The most effective treatments are those closest to this ideal position, while those farther from it are considered less desirable. For example, I1-H2, I1-H4, and I1-H5, followed by I1-H1 and I1-H3, are considered ideal treatments as they were closest to the perfect position. In contrast, I2-H1, followed by I2-H2, I2-H3, I2-H4, and I2-H5, were positioned farther from the ideal, making them the least desirable treatments in terms of both their distinguishing and typical abilities. Interestingly, all the ideal treatments were from irrigated conditions, indicating that the distinguishing potential of treatments was more evident under normal conditions. However, under stressful conditions, this ability decreased significantly. These ideal treatments can be viewed as ideotypes, demonstrating high performance across most traits. Nonetheless, challenges arise when associations between traits are not always significant. This issue is particularly relevant in camelina production, where both yield performance and quality characteristics are critical for achieving optimal outcomes. In this context, the use of multivariate statistical models with visual outputs becomes increasingly valuable for identifying the best treatments. Ultimately, the most effective treatments identified were I1-H2, I1-H4, and I1-H5, which involved the application of trifluralin, haloxyfop-R-methyl, and pinoxaden herbicides under irrigated conditions. In summary, irrigated treatments (I1-H2, I1-H4, and I1-H5) were the most effective, exhibiting strong correlations with high performance in traits like seed yield, thousand-seed weight, and plant height. Rainfed treatments showed reduced discriminative ability, with herbicides being less effective under these conditions due to lower herbicide absorption and reduced effectiveness of narrow-leaved weed control.

Yield evaluation

The effects of treatments on seed yield (SY) are illustrated in Figure 4A, where an axis representing SY is indicated with an arrow in its direction. Treatments I1-H3, I1-H4, and I1-H5, followed by I1-H2 and I1-H1, were the most effective for achieving high yield performance. In contrast, treatments I2-H1, followed by I2-H2, I2-H3, I2-H4, and I2-H5, were the least favorable for seed yield performance (Fig. 4A). It appears that the amount of available soil moisture influenced the effectiveness of herbicides by altering the morphological characteristics of crop plants. These changes can affect herbicide absorption, translocation efficiency, metabolism of toxic herbicide compounds (through the addition of functional groups), and the nature of the weed population, including weed biodiversity, plant density, and the dominance of specific weed species (Peerzada *et al.* 2021). The distance of treatments from the SY axis reflects the standard deviation, with smaller intervals indicating better consistency. Consequently, I1-H4 and I1-H5 exhibited smaller intervals and showed less variation, making them more reliable choices. In contrast, I2-H1 had lower seed yield performance (below the average, represented by the blue axis) and a larger interval from the SY axis, indicating greater variation, making it one of the least favorable treatments. The application of haloxyfop-R-methyl (H4) and pinoxaden (H5) under irrigated conditions led to an increase in seed yield, emphasizing the importance of effective weed control through the use of appropriate herbicides, as well as providing a suitable water supply. Considering the agro-climatic zone of the studied area and the common use of cycloxydim in onion fields, these two herbicides, haloxyfop-R-methyl and pinoxaden, are suitable options for herbicide rotation to prevent the emergence and spread of resistance to ACCase-inhibiting herbicides.

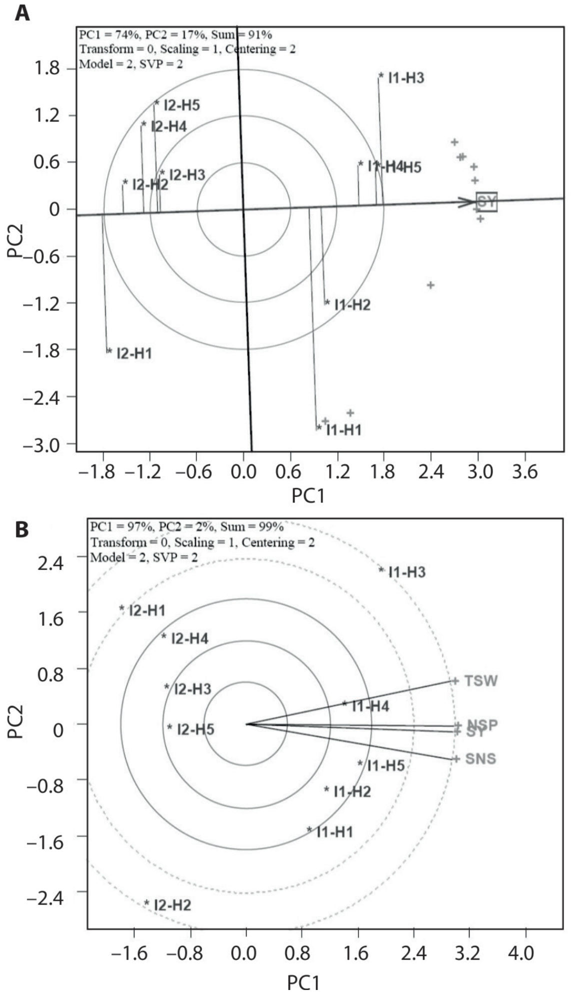

Fig. 4. A – reaction of various of treatments for seed yield (SY) performance and B – vector-option of biplot model showing relations between yield components in camelina. Treatments are: I1 – irrigated conditions; I2 – rainfed circumstances; H1 – no application of herbicide; H2 – trifluralin; H3 – cycloxydim; H4 – haloxyfop-R-methyl; and H5 – pinoxaden. Traits are: SY – seed yield; TSW – thousand-seed weight; SNS – seed number per silique; NSP – number of siliques per plant

Yield components

For camelina, three yield components are particularly important: thousand-seed weight (TSW), seed number per silique (SNS), and the number of siliques per plant (NSP). The related vectors display the relationships between these yield components (Fig. 4B), where seed yield is positively correlated with these components, especially the number of siliques per plant. Berti *et al.* (2011) identified the number of siliques per plant and thousand-seed weight as the most influential yield components in camelina, which is considered a promising alternative crop for farmers in South Central Chile. Similarly, Jiang and Caldwell (2016) found that seed yield in camelina was associated with the number of siliques per plant, thousand-seed weight, and siliques per unit area. Although the herbicides used in this study were effective in improving the growth and performance of camelina by controlling narrow-leaf weeds, the growth of broad-leaved weeds, such as herb-Sophia, shepherd's-purse, wild mustard, bastard cabbage, prickly lettuce, field bindweed, common fumitory, catchweed, and lady's thumb, remains a limiting factor for camelina growth. Therefore, the combined use of broadleaf and narrow-leaf herbicides is highly recommended in this region. However, considering the specific environmental conditions of semi-arid regions and the promising potential for expanding camelina cultivation, herbicide-free crop management should not be overlooked. Mixed cultivation of camelina with crops such as barley or peas, along with increased plant density per unit area and the use of mechanical control methods, has been suggested as an effective approach to improving camelina performance (Leclère *et al.* 2019). This study highlights the importance of irrigation in optimizing camelina performance and maximizing herbicide efficacy. Camelina producers in semi-arid or rainfed regions should consider the use of herbicides like trifluralin, haloxyfop-R-methyl, and pinoxaden under irrigated conditions for better weed control and higher yields. However, under rainfed conditions, producers may need to focus on more integrated approaches for weed management as herbicide effectiveness significantly drops. This further underscores the need for careful irrigation management and herbicide choice to enhance camelina production, particularly in regions where water availability is a limiting factor. Also, population assessment of weed species in the field showed that *Convolvulus arvensis*, *Lactuca virosa*, *Raphanus raphanistrum*, *Sisymbrium officinale*, *Capsella bursa-pastoris*, *Lepidium draba*, *Chenopodium album*, *Portulaca oleracea*, *Bromus tectorum*, *Hordeum jubatum*, and *Alhagi maurorum* had the highest population density and biomass after pesticide application.

This study revealed that certain herbicide and irrigation combinations were less effective in enhancing camelina growth and yield. Specifically, the rainfed treatments (I2) combined with herbicides H1 (no herbicide), H2 (trifluralin), H3 (cycloxydim), H4 (haloxyfop-R-methyl), and H5 (pinoxaden) showed the least favorable outcomes in terms of camelina performance. Among these, the combination of rainfed conditions with no herbicide application (I2-H1) resulted in the highest weed density and biomass, which significantly reduced camelina yield and growth parameters. Similarly, the treatments involving trifluralin (H2) and cycloxydim (H3) under rainfed conditions exhibited weaker performance than the same herbicides under irrigated conditions. These results underscore the necessity for adequate irrigation to optimize the efficacy of herbicide treatments and minimize weed competition, particularly in water-limited environments. The least effective herbicide and irrigation combinations, therefore, include all rainfed treatments, especially when paired with trifluralin, cycloxydim, haloxyfop-R-methyl, and pinoxaden. These combinations were shown to result in lower agronomic traits, including seed yield, number of siliques per plant, and seed number per silique, than treatments under irrigated conditions. While this study provides valuable insights into the interaction between herbicides and irrigation conditions for camelina cultivation, further research is needed to better understand the long-term impacts of different herbicide applications, particularly under rainfed conditions. In particular, research should explore alternative weed management strategies that are more effective in water-scarce environments, as well as the potential development of herbicide resistance in narrow-leaved weed species such as *Avena sterilis* and *Phalaris minor* under continuous use of ACCase-inhibiting herbicides. Additionally, studies investigating the optimization of irrigation techniques, combined with herbicide treatments, would be beneficial for maximizing camelina productivity in semi-arid and drought-prone regions. The potential for alternative herbicides or integrated weed management practices, including crop rotation and mechanical weed control, should also be explored to mitigate herbicide resistance.

Conclusions

Camelina cultivation under irrigated conditions with the application of cycloxydim (H3), haloxyfop-R-methyl (H4), and pinoxaden (H5), led to optimal performance in terms of seed yield, number of siliques per plant, and seed number per silique. These herbicides were found to be highly effective in controlling narrow-leaved weeds, thus reducing competition for water, nutrients, and light, which ultimately benefit the growth and productivity of camelina. In contrast, weed density and biomass were higher in treatments with no herbicide application, highlighting the importance of weed management in ensuring optimal plant growth. It is also important to note that overuse of ACCase-inhibiting herbicides (like cycloxydim, haloxyfop-R--methyl, and pinoxaden) could lead to resistance in certain weed species. To mitigate this, it is recommended to rotate herbicide types or combine them with other weed management strategies to prevent resistance buildup.

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