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Assessment of agronomic traits of safflower based on various planting arrangements and fertilizer application

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ABSTRACT The production of safflower in semi-arid regions is hindered by factors such as the poor quality of soils, low levels of organic matter, inadequate soil structure, deficiencies in essential nutrients, and insufficient information on effective agronomic practices. The current experiment aimed to investigate different planting designs (planting in-furrow with 40 cm or 60 cm inter-row spacing: IN40, IN60; or planting on the ridge with 40 cm or 60 cm inter-row spacing: ORI40, ORI60) and various fertilizer managements (C: control or no fertilizer application; CFW10 and CFW20: application of 10 or 20 t ha⁻¹ cow farm waste; NPK: application of primary macronutrient fertilizers including nitrogen, phosphorus, and potassium; and Fe+Zn: application of trace elements iron and zinc) on the agronomic characteristics of safflower in the Razan region, Hamedan, Iran. Application of CFW reduced the days to seedling emergence by 40% compared to the control. The ORI60 planting design accelerated the phenological development of the plant, and this effect was more evident under CFW application. The longest time to maturity was observed under the no-fertilizer condition. The tallest plants were obtained with CFW20 + ORI60. Although all fertilizer applications improved lateral growth and the number of branches, the greatest effect was recorded with CFW20 + ORI60. A similar trend was observed for the number of capitula. However, the highest number of achenes per plant was obtained with the application of CFW or Fe+Zn using the IN60 planting design. Application of CFW+IN60 or micronutrients+ORI60 accelerated ground coverage by the canopy. The highest biological yield and seed yield were achieved with CFW20+IN40. Overall, the results showed that the efficiency of organic fertilizers was more evident than that of chemical fertilizers, and planting in-furrow with low inter-row spacing (higher plant density) improved safflower performance.

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Introduction

Safflower (*Carthamus tinctorius* L.) belongs to the Compositae family and is recognized as either an oilseed crop or a source of dye (dyer's saffron). This plant exhibits high productivity and demonstrates relative tolerance to environmental stresses, making it well-suited for semi-arid regions. Safflower is an annual herb that possesses green and tender foliage during its vegetative stage, while its stems become tough and woody by the end of its reproductive phase. The plant develops a deep root system, reaching depths of up to two meters, which helps it partially cope with water scarcity in the upper soil layers. Nevertheless, due to a lack of knowledge regarding cultivation practices and the absence of ongoing breeding programs, safflower is currently an underappreciated or neglected oilseed crop. The amount of oil extracted from safflower ranks eighth among oilseed plants (de Oliveira Neto et al. 2022).

Although archaeologists and plant evolutionists believe that safflower was domesticated and evolved in Western Asia and North Africa, specifically the Fertile Crescent (Gomashe et al. 2021), its current cultivated area in these regions is not large. Global safflower seed production is 995,507 t, with an estimated cultivated area of about 1.2 million hectares. In Iran, the cultivated area of this plant is very limited, estimated at 4,000 ha, and about 5,000 t of safflower seed is harvested from these areas (FAOSTAT 2022). However, safflower is a rich source of α -tocopherol and carthamin, and it is a multi-purpose plant used for extracting oil, as well as medicinal and culinary compounds. It can also be utilized in the cosmetics industry or for biodiesel production. Furthermore, due to safflower's adaptability to water scarcity, it can be an ideal and strategic crop option to address climate change in semi-arid regions (Ekin 2005).

The soil in semi-arid regions encounter significant challenges. A noticeable decline in annual rainfall over

recent decades, uneven rainfall distribution during the growing season, a sharp rise in temperatures from early to mid-summer, improper cropping practices, unsuitable crop rotations, overgrazing of crop residues, and the collection or incineration of residues have all led to a considerable reduction in soil organic matter in these areas (Bodner et al. 2015). Additionally, the elevated pH levels in the soil, the high concentration of calcium carbonate, and the excessive application of phosphate fertilizers have greatly hindered the uptake of micronutrients, particularly iron and zinc (Bolan et al. 2023). Soil nutrient status can affect both the quantity and quality of oilseed crops (Pasandi et al. 2018). The use of organic fertilizers and improvement of soil organic matter can facilitate water absorption in the soil and increase root access to stored water in the rhizosphere. Additionally, by increasing water holding capacity, the concentration of salt and harmful compounds can be reduced, and their negative effects are alleviated through organic fertilizer application. Besides providing nutrients, organic materials have beneficial effects on soil microbiomes and physico-chemical characteristics. Animal manure is an inexpensive and readily available source of organic matter and a good alternative to chemical fertilizers. In the semi-arid regions of northwestern Iran, the use of animal manure significantly increased both vegetative growth (such as stem elongation, canopy width, and lateral growth) and achene yield of safflower (Janmohammadi et al. 2016). In soils characterized by a heavy clay texture, applying organic soil amendments can enhance soil aggregation, boost porosity and hydraulic conductivity, improve penetrability and soil aeration, and promote greater root density and depth (Dong et al. 2022). Conversely, in sandy soils, the use of animal manure enhances the capacity for water and nutrient retention, creating relatively favorable environmental conditions in the rhizosphere for root development (Bationo et al. 2005).

Due to the specific conditions of soil in arid and semi-arid areas, deficiencies of micronutrients such as iron and zinc are more widespread. The roles of iron and zinc as enzyme cofactors and as components of important physiological molecules highlight the need for accurate and sufficient supply of these elements for plant growth (Rai et al. 2021). In addition to the impact of nutritional management on the growth and performance of safflower, adjusting plant density, inter-row spacing, and planting patterns

(such as planting position on the ridge, in the furrow, or flat planting) can significantly affect the growth of this crop. However, comprehensive information on the effects of planting patterns under different fertilizer conditions on the agronomic characteristics of safflower is still lacking. Given the compensatory relationships among achene yield components, investigating the effects of inter-row spacing and plant density is particularly important. This experiment aimed to examine the application of various organic and chemical (macro- and micronutrient) fertilizers on the agronomic characteristics of safflower grown in the Razan region of Hamadan.

Materials and methods

Study site, climate, and soil characterization

This research was conducted during the 2022-2023 growing season in a private field located in the suburbs of Razan, Hamedan, Iran (35.39° N, 49.03° E, at 1,825 meters above sea level). According to the De Martonne classification, the climate of the study area is cold and semi-arid. The area has an average annual precipitation of 392 mm and an average yearly temperature of 11 °C. Before the experiment began, one composite soil sample was collected from depths of 0-30 cm and 30-60 cm, and its physical and chemical properties were measured (Table 1).

Experimental design, treatments, and plot layout

The field experiment was arranged as a split-plot in a randomized complete block design with three blocks (replications). Fertilizer management was allocated to main plots (whole plots) within each block, and planting pattern was allocated to subplots within each main plot. Main plots were separated by 1.5 m buffer strips to minimize nutrient movement between adjacent treatments. Each subplot measured 3.0 m × 2.5 m. Within each block, fertilizer treatments were randomized to main plots; within each main plot, planting patterns were randomized to subplots. The subplot (i.e., each fertilizer × planting pattern combination within a block) was considered the experimental unit for all statistical analyses. Treatments comprised five fertilizer managements (C: no fertilizer; CFW10 and CFW20: 10 or 20 t ha⁻¹ cow farm waste; NPK: urea + triple superphosphate + potassium sulfate; Fe+Zn: Fe and Zn nanoparticles chelated on EDTA)

Table 1. Soil properties and soil-available nutrients at the study site (Razan, Iran).

Soil texture	Sand (%)	Silt (%)	Clay (%)	CaCO ₃ (%)	Zn (ppm)	Fe (ppm)	Organic matter (%)	EC (dS m ⁻¹)	pH	CEC (Cmolc/kg)	K (mg/kg)	P (mg/kg)	N (%)
Clay loam	21	36	43	14%	0.43	0.79	0.41	1.38	7.54	21.2	287.3	14.8	0.12

and four planting patterns (in-furrow with 40 or 60 cm inter-row spacing: IN40, IN60; on-ridge with 40 or 60 cm inter-row spacing: ORI40, ORI60).

Field operations, crop establishment, fertilization, and irrigation management

Cow farm waste was collected from the feedlot cattle farm. The chemical characteristics of the applied animal manure were as follows: 69.48% organic matter, 2.61% nitrogen, 1.05% phosphorus, 3.16% potassium, 1.36% calcium, 0.61% magnesium, 0.59% sulfur, 215 mg kg⁻¹ zinc, 129 mg kg⁻¹ iron, 82 mg kg⁻¹ manganese, with an EC of 5.72 dS m⁻¹ and a pH of 7.5. Cow farm waste was stored in the holding pond for 4 months to allow for proper decomposition and reduction of pathogen load. Initial plowing and primary tillage were performed with a reversible moldboard plow in December 2022. After soil planking and clod crushing with a disc harrow, the main plots were marked using a border disc. Cow farm waste was applied to the main plots and mixed with the topsoil using a manually started mini rotavator tiller. In the third decade of February 2023, furrows and ridges with the previously described features were constructed and prepared in the sub-plots using a mini-tiller furrowing machine. Safflower (*Carthamus tinctorius*) seeds of the "Saffeh" variety were obtained from Pakan Bazar Company, Isfahan, Iran. Seeds were manually sown on March 15 at a 4 cm spacing, either in-furrow or on ridges, in 3 cm deep holes. To achieve the desired final density, seeds were hand-planted as clumps of two seeds per hole, and after seedling emergence and establishment, the planting rows were thinned. NPK was provided by applying urea (220 kg ha⁻¹), triple superphosphate (190 kg ha⁻¹), and potassium sulfate (80 kg ha⁻¹). All phosphate and potassium fertilizers and one-third of the nitrogen fertilizer were applied at planting, with the remaining nitrogen fertilizer applied at the main stem elongation stage (BBCH 30) and at the beginning of capitulum formation (BBCH 50). Fe+Zn fertilizer contained iron and zinc nanoparticles chelated on EDTA (Sepehr Paramis, Iran), which placed in a "band" 3 cm down from the seed during planting. The amount of Fe+Zn fertilizer used was 2 kg ha⁻¹, as recommended by the manufacturer.

To determine the gravimetric soil water content (GSWC) at field capacity, 24 h after irrigation, samples were taken from depths of 30 and 60 cm using an auger. The moisture content was measured with a pressure plate apparatus under a suction of approximately 0.3 atm. GSWC at field capacity at depths of 30 and 60 cm was 21% and 26%, respectively. To determine irrigation dates, external plant indicators and weather conditions were considered.

Irrigation was applied using a drip tape system and

polyethylene pipes under pump pressure. The required irrigation volume was calculated using the following equation and volumetric meters:

$$V = (FC - \theta_m) \times GS \times D_{root} \times A / E_i \text{ (Kirkham 2023),}$$

where V is the volume of irrigation water (m³), FC is the GSWC at field capacity, θ_m is the GSWC before irrigation, GS is the apparent specific gravity of the soil (g cm⁻³), D_{root} is the rooting depth (60 cm in this experiment), A is the irrigated area (m²), and E_i is the irrigation efficiency (90%). The estimated volume of water was distributed uniformly using volumetric meters. On average, at the beginning of the growth period, irrigation intervals were 10 days, decreasing to 4 days as daily temperatures increased.

Before planting, Treflan herbicide (liquid EC) was applied to dry soil at a rate of 2 L ha⁻¹. At the beginning of the flowering phase, the safflower bud fly (*Acanthiophilus helianthi*) was controlled using Matasystox and Diazinon pesticides (0.2% v/v). To estimate the phenological and developmental stages of safflower planting, the fields were monitored daily and the developmental stage was recorded.

Measurements and statistical analysis

Leaf chlorophyll content was measured with a SPAD-502Plus chlorophyll meter (Konica Minolta, Tokyo, Japan) in the middle of the flowering stage (BBCH 65, 50% of florets open). Phenological traits were recorded as the number of days from sowing to seedling emergence (DTE), to initiation of flowering/appearance of the main capitulum (DBF), and to full maturity (DTM).

At full maturity, a 1 m² quadrat was placed in the central area of each subplot to avoid border effects. Plants within the quadrat were harvested at the soil surface and oven-dried at 60 °C to constant mass to determine aboveground dry biomass (biological yield). Yield components were assessed from plants sampled within the same quadrat, including number of capitula per plant, capitulum diameter, capitulum weight, achene weight per capitulum, and number of achenes per capitulum; subsamples taken within a subplot were averaged to obtain a single value per subplot. Ground cover by canopy (%) was estimated visually at the end of the capitulum development stage by assessing the proportion of bare soil within the 1 m² quadrat and subtracting this value from 100. Canopy width was measured as the horizontal spread of the foliage (left-to-right) using a measuring tape. After threshing, the weights of husk and other residues were recorded together with yield components.

Data were analyzed by ANOVA appropriate for a split-plot design using SAS software, with blocks as random

Table 2. Effects of fertilizer management and planting patterns on selected agronomic traits of safflower.

		DTE	DBF	DTM	CHL	TCN	TAW	DPC	GCP	HI
C	IN ₄₀	9.00 ^a	90 ^a	120 ^f	47.13 ^{def}	13.33 ^g	11.83 ^{gh}	2.30 ^{ef}	95.00 ^c	26.80 ^{fg}
	IN ₆₀	9.00 ^a	89 ^b	120 ^f	45.03 ^f	15.00 ^{fg}	13.667 ^{fg}	2.43 ^{de}	94.00 ^{cd}	26.60 ^{fg}
	ORI ₄₀	9.00 ^a	90 ^a	118 ^g	49.50 ^{bcdef}	13.33 ^g	11.03 ^h	2.43 ^{de}	92.00 ^e	29.20 ^{de}
	ORI ₆₀	9.00 ^a	90 ^a	118 ^g	46.67 ^{ef}	15.66 ^{efg}	13.30 ^{fg}	2.47 ^{de}	88.67 ^{de}	30.63 ^{bcd}
CFW10	IN ₄₀	6.00 ^e	88 ^c	126 ^c	53.17 ^{abc}	20.33 ^{cdef}	17.00 ^e	2.70 ^{ab}	96.33 ^{ab}	32.9 ^b
	IN ₆₀	6.00 ^e	88 ^c	126 ^c	56.33 ^{ab}	22.33 ^{bcd}	19.63 ^d	2.67 ^{ab}	94.67 ^b	28.13 ^{de}
	ORI ₄₀	5.00 ^f	88 ^c	126 ^c	48.60 ^{cdef}	20.33 ^{cdef}	20.10 ^{cd}	2.67 ^{abc}	93.33 ^{de}	28.40 ^{def}
	ORI ₆₀	6.00 ^e	87 ^d	126 ^c	52.27 ^{abcde}	21.00 ^{cdef}	19.23 ^d	2.67 ^{abc}	93.33 ^{de}	32.23 ^b
CFW20	IN ₄₀	5.00 ^f	85 ^f	130 ^a	49.63 ^{bcdef}	32.33 ^a	21.00 ^{cd}	2.83 ^a	100.00 ^a	31.96 ^{cd}
	IN ₆₀	4.00 ^g	84 ^g	130 ^a	52.87 ^{abcd}	33.66 ^a	23.13 ^{bc}	2.63 ^{abc}	98.33 ^{ab}	36.91 ^a
	ORI ₄₀	4.00 ^g	83 ^h	128 ^b	49.83 ^{bcdef}	28.00 ^{ab}	25.57 ^{ab}	2.76 ^{ab}	97.00 ^b	32.77 ^b
	ORI ₆₀	5.66 ^f	83 ^h	128 ^b	53.17 ^{abc}	28.00 ^{ab}	27.03 ^a	2.96 ^a	96.33 ^{bc}	31.97 ^{cd}
NPK	IN ₄₀	9.00 ^a	87 ^d	126 ^c	58.23 ^a	21.00 ^{cdef}	16.00 ^e	2.60 ^{bcde}	93.00 ^{de}	30.00 ^{de}
	IN ₆₀	8.00 ^d	87 ^d	126 ^c	54.87 ^{ab}	25.33 ^{bc}	16.96 ^e	2.60 ^{bcde}	95.33 ^c	34.03 ^a
	ORI ₄₀	8.00 ^d	87 ^d	126 ^c	59.43 ^a	19.66 ^{cdef}	16.86 ^e	2.50 ^{cde}	94.00 ^{cd}	31.8 ^{bcd}
	ORI ₆₀	8.33 ^c	86 ^e	126 ^c	56.27 ^{ab}	20.33 ^{cdef}	19.43 ^d	2.71 ^{ab}	85.33 ^g	34.53 ^a
Fe+Zn	IN ₄₀	8.67 ^b	87 ^d	124 ^d	45.00 ^f	21.33 ^{cde}	19.26 ^d	2.73 ^{ab}	95.00 ^c	28.03 ^{def}
	IN ₆₀	8.00 ^d	86 ^e	124 ^d	53.70 ^{abc}	24.66 ^{bc}	16.31 ^{ef}	2.67 ^{ab}	94.33 ^{cd}	36.56 ^a
	ORI ₄₀	8.00 ^d	85 ^f	122 ^e	52.83 ^{abcd}	20.33 ^{cdef}	19.00 ^d	2.67 ^{abc}	94.33 ^{cd}	26.63 ^{fg}
	ORI ₆₀	9.00 ^a	85 ^f	122 ^e	51.73 ^{abcde}	21.33 ^{cde}	16.30 ^{ef}	2.67 ^{abc}	89.00 ^f	29.03 ^{de}
		P value								
Block		0.768	<.0001	0.841	0.671	0.849	0.4212	0.536	0.1308	0.3602
Fertilizer		0.001	<.0001	0.001	0.003	0.005	0.001	0.002	0.0011	0.0007
Block×Fertilizer		0.685	0.649	0.361	0.429	0.658	0.4781	0.632	0.4547	0.7764
Planting pattern		0.045	0.031	0.065	<.0001	0.014	<.0001	0.210	0.354	<.0001
Fertilizer×Planting pattern		0.001	0.204	0.041	0.065	0.029	0.014	0.341	0.0019	0.065

Fertilizer (F): C, no fertilizer; CFW10 and CFW20, cow farm waste at 10 or 20 t ha⁻¹; NPK, urea (220 kg ha⁻¹) + triple superphosphate (190 kg ha⁻¹) + potassium sulfate (80 kg ha⁻¹); Fe+Zn, Fe and Zn nanoparticles chelated on EDTA (2 kg ha⁻¹, banded 3 cm below the seed at sowing). Planting pattern (P): in-furrow planting with 40 or 60 cm inter-row spacing (IN40, IN60) or on-ridge planting with 40 or 60 cm inter-row spacing (ORI40, ORI60). Traits: DTE, days to emergence; DBF, days to initiation of flowering (appearance of the main capitulum); DTM, days to maturity; CHL, leaf chlorophyll content (SPAD units); TCN, number of capitula per plant; TAW, achene weight per plant (g); DPC, capitulum diameter (cm); GCP, ground cover by canopy (%); HI, harvest index (%). Within each column, means followed by different letters differ significantly (LSD, P ≤ 0.05).

effects. The statistical model was $y_{ijk} = \mu + B_i + F_j + (B \times F)_{ij} + P_k + (F \times P)_{jk} + \epsilon_{ijk}$, where B is block (random), F is fertilizer (main-plot factor), P is planting pattern (subplot factor), (B×F) is the main-plot error term, and ϵ is the subplot (residual) error. Fertilizer effects were tested against the main-plot error (block × fertilizer), whereas planting pattern and fertilizer × planting pattern effects were tested against the subplot (residual) error. When F-tests were significant, means were separated using the LSD test at P ≤ 0.05. Principal component analysis (PCA) biplots were prepared in Statistica, and box plots were produced in SPSS.

Results

ANOVA for phenological stages indicated that fertilizer

management had a significant effect on these parameters. However, planting design was significant only for the number of days to seedling emergence and the number of days to initiation of flowering (Table 2).

The fastest seedling emergence occurred with the application of CFW20 and sowing in the furrow with 60 cm inter-row spacing (IN60), planting on the ridge with 40 cm inter-row spacing (ORI40), or planting on the ridge with 60 cm inter-row spacing (ORI60). In contrast, plants grown without fertilizer application or with Fe+Zn application using the ORI60 planting design had the longest seedling emergence time. Application of CFW20 with on-ridge planting resulted in the earliest flowering, while plants grown without fertilizer application showed the latest flowering (89.75 days) (Table 2).

Application of CFW, NPK, and Fe+Zn decreased the number of days to flowering compared to control. The

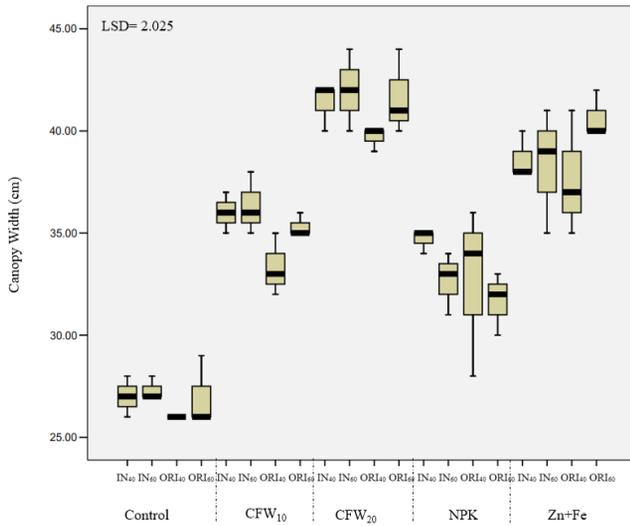


Figure 1. Effects of fertilizer management and planting pattern on safflower canopy width in the Hamadan region (Iran). Treatment codes: C, no fertilizer; CFW10 and CFW20, cow farm waste at 10 or 20 t ha⁻¹; NPK, macronutrient fertilizer (urea + triple superphosphate + potassium sulfate); Fe+Zn, Fe and Zn nanoparticles chelated on EDTA. Planting patterns: IN40 and IN60, in-furrow planting with 40 or 60 cm inter-row spacing; ORI40 and ORI60, on-ridge planting with 40 or 60 cm inter-row spacing. Among boxes, differences greater than the LSD indicate significant differences ($P \leq 0.05$).

application of animal manure at high levels significantly increased the number of days to full maturity. The highest number of days to maturity was recorded under CFW20+IN40 or IN60, while the plants grown without fertilizer and planted top of the ridge showed the earliest maturity with 118 days. The main effects of fertilizers and planting patterns on chlorophyll content were significant and the lowest amount of chlorophyll was observed in planting in the furrow with inter-row distance 40 cm. Among the examined fertilizers, application of NPK increased the chlorophyll content by 19% compared to the control, while the application of Fe+Zn, CFW20, and CFW10 increased the amount of this pigment by 7%, 11%, and 8% compared to the control.

The estimation of the canopy width as an important vegetative and lateral growth parameter indicated that the use of fertilizer at a statistical level of 1% and planting patterns at a statistical level of 5% affected this component. The widest canopy was recorded in CFW20 with ORI40 or ORI60 planting design, which was 53% more than the plants grown under no fertilizer application. The plants grown under the application of Fe+Zn with ORI60 planting design were in the next rank. However, the influence of planting patterns was different in diverse fertilizer conditions. Under CFW applied conditions the plants sown in the furrow showed a higher canopy width

than plants grown on ridge (Fig. 1).

The evaluation of the number of capitula per plant as one of the most important components of achene yield indicated that the mutual effects of fertilizer × planting design were significant at the 5% level. The plant grown under CFW20+IN40 or IN60 showed the highest number of capitula. Comparisons between types of planting patterns showed that planting in the furrow was about 12% higher than other planting methods. The lowest number of capitula was recorded under the conditions without fertilizer use and on-ridge planting with 40 cm inter-row spacing (Table 2). The results showed that optimal fertilizer management with the use of CFW and planting in the furrow increased the number of capitula per plant by 86% compared to control. The application of NPK, Fe+Zn with IN60 planting pattern increased the number of capitula by 63% and 49%, respectively, compared to the control.

Achene weight was affected by fertilizer management and planting patterns, and the highest achene weight was recorded in plants grown in CFW20+ORI40 or ORI60. Although all the applied fertilizers increased the weight of achene, the most improving effect was observed with the use of animal manure, and the utilization of NPK and Fe+Zn were the next rank of effectiveness. Although there was no significant difference in terms of achene weight between planting patterns under chemical fertilization, plants grown in wider distances had more achene weight under CFW applied conditions (Table 2).

Valuation of the plant dry mass of the whole plant (biological yield) indicated that the application of CFW increased this component by 40% compared to the control.

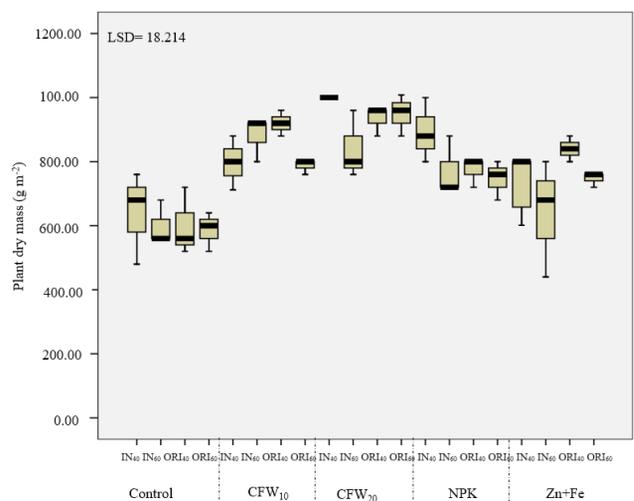


Figure 2. Effects of fertilizer management and planting pattern on safflower aboveground dry mass (biological yield) in the Hamadan region (Iran). Treatment codes and planting pattern abbreviations are as in Fig. 1.

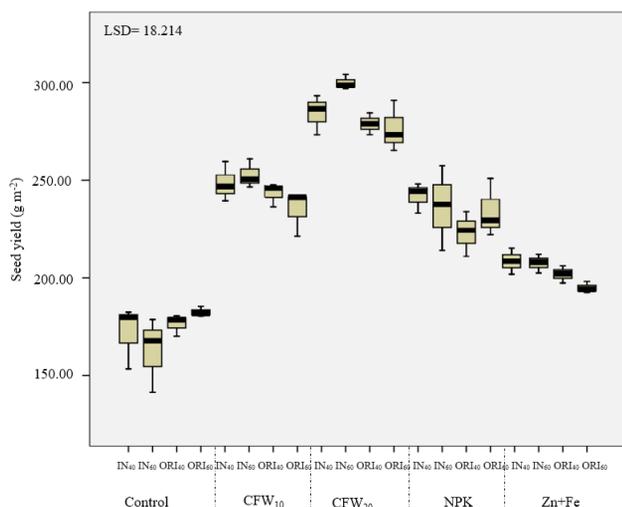


Figure 3. Achene yield of safflower as affected by fertilizer management and planting pattern in the Hamadan region (Iran). Treatment codes and planting pattern abbreviations are as in Fig. 1.

The highest plant weight was observed in CFW20+IN40 conditions, which was not significantly different from CFW20+ ORI40 or ORI60. In this regard, it was observed that the application of NPK+IN40 on vegetative growth was different from other planting patterns under the application of this fertilizer and it increased the biological yield by about 33% compared to the control. Meanwhile, under the Fe+Zn applied conditions, ORI40 planting design had a prominent improving effect on this parameter (Fig. 2).

The use of fertilizers increased the capitulum diameter. The smallest diameter of the capitulum was observed under the control condition (2.43 cm) and the largest diameter was recorded in plants grown under the application condition of CFW20 (2.75 cm), Fe+Zn (2.68). The application of macronutrient chemical fertilizer increased the capitulum diameter by 5% compared to the control. Measuring the percentage of ground cover by canopy showed that planting under CFW20+ IN40 produced the highest amount of ground coverage. Applying planting pattern IN40 significantly accelerated the ground cover by canopy. The evaluation of achene performance showed that the highest amount of achene was obtained under the conditions of CFW20 application by planting in the furrow, and the plants grown under CFW10 and NPK were in the next position (Fig. 3).

Fertilizer application increased achene yield by 85% compared to the control, and its improving effect was much more evident than planting patterns. Regardless of the type of chemical or organic fertilizer, under the conditions of using fertilizer, planting inside of the furrow increased achene yield. Two-dimensional principal

component analysis (PCA) was used for vector dispersion and relationships between agronomic traits. A positive correlation was shown through proximity and small angles between traits ($\cos 0^\circ$ is +1), and a negative correlation was shown between traits with an angle of 180° ($\cos 180^\circ$ is -1). The results indicated that there was a positive and significant correlation between achene yield, number of seeds in the capitulum, number of seeds in secondary capitula, the weight of seeds in the secondary capitula, number of capitulum, the weight of capitulum shell and total plant dry mass. Application of CFW₂₀ along with different plant patterns was very close to the mentioned traits and this means that they have had the most improving effect on the traits mentioned. The yield of achene showed a negative correlation with the number of days to seedling emergence and the percentage of unfilled achene (Fig. 4).

Cluster analysis of the combined treatments (different fertilizer and planting patterns) based on similarity in influencing the evaluated traits divided the combination treatments into three clusters. Cluster 1: including control (no use of fertilizer) along with different planting patterns that had the least positive effect on the evaluated traits. The second cluster included the use of chemical fertilizers (NPK and Fe+Zn) and CFW10 in different

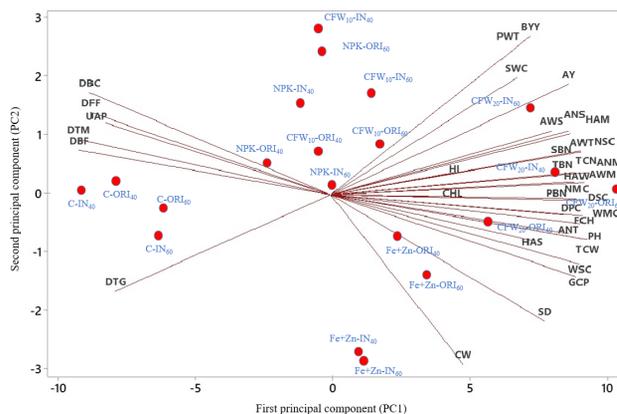


Figure 4. Principal component analysis (PCA) biplot showing relationships among agronomic traits of safflower and the position of fertilizer x planting pattern treatments. Fertilizer and planting pattern codes are as in Table 2. Trait abbreviations: BYY, biological yield; DTG, days to emergence; DBC, days to capitulum formation; DBF, days to initiation of flowering; DFF, days to full flowering; DTM, days to maturity; CHL, leaf chlorophyll content; CW, canopy width; PH, plant height; FCH, height of the first capitulum; SD, stem diameter; DCP, diameter of the main capitulum; DSC, diameter of the secondary capitulum; TCN, number of capitula per plant; TAW, achene weight per plant; DPC, capitulum diameter; GCP, ground cover by canopy; HI, harvest index; TBN, total number of branches; UAP, percentage of unfilled achenes; ASW, seed weight in the secondary capitulum per plant; TCW, capitulum weight per plant.

inter-row spacing and planting in in the furrow or top of the ridge, which were ranked second in terms of affecting the agronomic traits. Cluster 3 included the application of high levels of CFW in different planting patterns, which had the greatest effect, especially in planting in the furrow. This cluster had the greatest impact on the evaluated agronomic traits (Fig. 5).

Discussion

According to the soil chemical analysis, severe nutrient deficiencies were evident in the investigated area, and the percentage of soil organic matter was extremely low. The results showed that among the evaluated fertilizers, CFW20 had the most positive effect on growth and achene yield. These beneficial effects can be attributed to improvements in soil physicochemical properties. Given the soil characteristics of semi-arid areas and certain existing limitations, the use of CFW can enhance soil water-holding capacity, nutrient balance, and the ability to retain or exchange nutrients – benefits that cannot be achieved with chemical fertilizers alone (Naorem et al. 2023). In this experiment, the use of micronutrient and macronutrient chemical fertilizers alone did not significantly stimulate vegetative growth or reproductive components, indicating that organic soil amendment is necessary before applying chemical fertilizers. A brief comparison of different levels of CFW indicated that using 10 t ha⁻¹ is probably not sufficient to improve the soil in the mentioned area, and a positive plant response to CFW occurs only with at least 20 t ha⁻¹. Reducing inter-row spacing and increasing plant density per unit area increased some vegetative components, such as plant height. The results also showed that in rows with 40 cm spacing, lateral growth decreased significantly. These findings are consistent with those of Hamza (2015), who reported that increasing plant density per unit area decreased the number of lateral branches, number of capitula per plant, petal yield per plant, and oil percentage. However, increasing density raised achene yield and oil yield per unit area.

On the other hand, it has been determined that there is a compensatory effect between the components of safflower yield, and the decrease of one component under reduced density conditions may be compensated by the increase of the other component, and this caused an increase in achene yield in rows with 40 cm intervals. A decrease in the main yield components such as the number of capitulum per plant was observed under some narrow planting rows, but this decrease was compensated for increasing the number of plants per unit area. It seems that the increase in inter-row spacing has intensified the intra- and inter-plant competition (Ameyu and Tesfaye

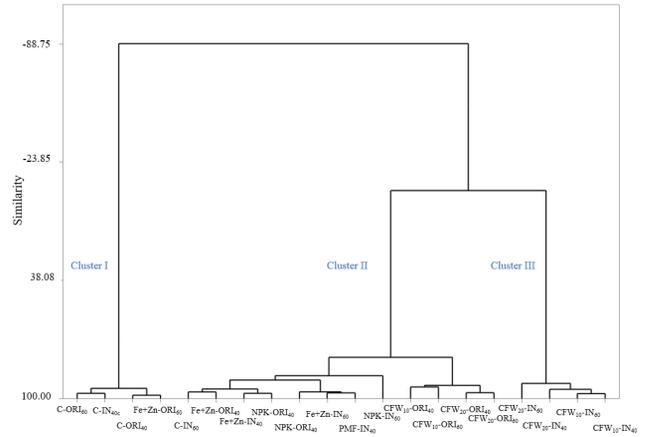


Figure 5. Cluster analysis (dendrogram) of fertilizer × planting pattern combinations based on similarity in the evaluated agronomic traits of safflower.

2020) and has reduced the yield by reducing the number of secondary capitulum and increasing the number of infertile capitulum or increasing the portion of unfilled achenes.

The yield of an individual plant was strongly influenced by the planting patterns. This response was due to the reduction of some of the yield components, including the number of capitula per plant and the number of seeds per capitulum, as inter-row spacing increased. Our results confirm the findings of a previous study on the effects of density and inter-row distances in safflowers (Pourhadian and Khajepour 2009).

Planting in-furrow had better consequences compared to planting on the ridge, it seems that the accumulation of more organic matter in the bottom of furrows after utilization of CFW, harvesting and re-directing precipitation into the furrows, and protecting the seedlings from cold winds at the initiation of the growing season and the better establishment of seedlings are among the reasons that have led to the superior planting in-furrow. It should be noted that a large increase in inter-row spacing probably increases the competition between plants on the rows, and this may cause inefficient use of light, stimulate vegetative growth, and change the pattern of photoassimilate partitioning for the vegetative parts and the production of infertile branches. On the other hand, due to the climate of the region and the scarcity of water resources, the gap between the rows and exposing bare ground to solar radiation leads to soil moisture loss through an increase in evaporation. In the present experiment, planting in-furrow with 40 cm inter-row spacing produced a higher achene yield. Planting in-furrow with 40 cm inter-row spacing, combined with the application of CFW20, significantly increased achene

yield compared to the no-fertilizer condition. The effects of manure application were more significant than those of planting patterns, and the low soil organic matter is likely an important limiting factor for safflower growth in semi-arid areas. The use of organic fertilizers can improve the physical and biological properties of the soil, in addition to supplying essential nutrients to the plant (Nouraein et al. 2019).

Conclusions

This study explored how organic amendments, chemical fertilizers, and planting arrangement affect the growth and yield of safflowers in a semi-arid environment. The results indicated that using organic fertilizers, particularly in higher amounts, is crucial for enhancing safflower yield. The analysis demonstrated that in the area examined, planting with an in-furrow inter-row spacing of 40 cm combined with high levels of animal manure produced the most favorable results. The beneficial effects of animal manure on the growth and yield of achene were significantly greater than those of either macro or micronutrient chemical fertilizers. Our findings highlighted the importance of improving the physical and chemical soil conditions before applying chemical fertilizers. However, the effects of manure application and planting patterns on the rhizosphere environment and the interaction between the root system and soil still need more accurate investigation. The details of how manure application affects the physical and chemical properties of the soil are still not well understood. Given the poor soil in the region, organic amendments using animal manure, which is a cheap, relatively available, and highly effective fertilizer source, should be included in regional macro policies.

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