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Wheat performance is affected by the substitution of chemical fertilisers with animal manure under different soil moisture regimes

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The intensification of the effects of climate change and the necessity of using climate-resilient methods and improving nutritional conditions, replacing chemical fertilisers with organic fertilisers and saving water consumption should be heightened in semi-arid regions. A field experiment was conducted to evaluate the effect of different doses of NPK chemical fertilisers (CH_0: no use of NPK fertiliser, $CH_{50:}$ application of 50% of the recommended dose of NPK, CH_{100}: application of 100% of the recommended dose of NPK) and different levels of animal manure (0, 5, and 10 t ha^{-1}: FYM_0, FYM_5 and FYM_{10}) under different soil moisture conditions (full irrigation (FI) and rainfed with one supplementary irrigation at the spike stage (SI)) on winter wheat performance in Hamedan area. Under FI conditions, the lateral growth of the canopy increased strongly with the use of chemical fertilisers. However, the longitudinal growth and internode distances increased with the combined application of chemical and organic fertilisers. Under SI, the application of FYM_{10} + CH_{50} had a greater effect on yield components. Grain weight decreased under both irrigation regimes with the increase in the consumption of NPK fertilisers. The highest grain yield (4790 kg ha^{-1}) was obtained for plants grown under FI + FYM_{10} + CH_{100} and plants grown with FYM_{10} + CH_{50} (4425 ha^{-1}). Under the SI conditions, the highest yield was recorded with the utilization of FYM_{10} + CH_{50} (2644), and FYM_{10} + CH_0 (2549), and the lowest yield was recorded under FYM_0. Taken together, the use of chemical fertilisers under FI conditions is inevitable to increase the grain yield, and the replacement of NPK fertiliser with the current applied amounts of animal fertilisers could not be adequate to improve the grain yield considerably.

Keywords: full irrigation, organic fertiliser, spike length, tiller number, *Triticum aestivum*, vegetative growth, water deficit stress

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INTRODUCTION

Common wheat (*Triticum aestivum*) is one of the most important and strategic crops in the semi-arid regions (Briak, Kebede, 2021). This plant has a relatively high adaptability to the climatic conditions of the semi-arid regions, so in many areas of West Asia to North Africa (WANA), most agricultural production systems are based on cereals such as wheat and barley (Savin et al., 2022). Crop rotation in most of the rainfed fields in these areas is carried out only by repeatedly cultivating plants such as wheat, barley, and fallow, without the presence of other crops. This type of inflexibility in introducing other plants into rotation and major reliance on winter cereals has made the system fragile against climate change and has also led to a continuous decline in soil organic matter (Liu et al., 2022). Although wheat plants are inherently tolerant to some extreme conditions and the breeding processes carried out to improve resistance to environmental stresses, the level of wheat production in these areas is still strongly determined by the availability of water, the amount of available moisture in the soil, and some climate resilient management (Mao et al., 2023; Janmohammadi, Sabaghnia, 2023).

The area under wheat cultivation in the world is 260 million hectares, and wheat production in 2023 is estimated to be about 791 million tonnes. The area under wheat cultivation in Iran is 6.2 million hectares, and the amount of wheat harvested is about 14.5 million hectares. In Iran, about 45% of the total wheat produced is harvested from rainfed systems (FAOSTAT, 2024). Hamedan Province is considered one of the most important producers of rainfed wheat in Iran, producing 9% of the total rainfed wheat production (Mosammam et al., 2016). In addition to soil moisture, one of the important factors affecting wheat yield is plant nutritional management. Although about half of the wheat produced in Iran is harvested from rainfed systems, these areas are often semi-arid and have irregular, scattered, unpredictable rainfall and relatively unfavourable soil conditions. The amount and pattern of precipitation have been such that it has resulted in poor soil development, and due to low natural vegetation production and excessive grazing, the fertility of the soils in these areas is also low (Karandish et al., 2022). A simple definition of soil fertility is the ability of the soil to provide conditions that support crop growth and produce high and sustained yields. The effect of fertility can also be interpreted as improving the quality of agricultural products so that they meet the nutritional needs of humans or livestock. Fertility can also be defined as providing adequate plant nutrition. The soils of these areas are relatively shallow with an incomplete development process, high pH, low organic matter content, low water retention capacity, low cation exchange capacity, and low availability of nutrients to plant roots. The soils of these areas have a weak structure, mostly clayey and dense textures, show high levels of crusting, and are characterised by clod formation after plowing (Mattila, Vihanto, 2024).

Although the discovery of short-lived genes paved the way for the use of greater amounts of chemical fertilisers during the Green Revolution, this development led to an increase in the area under cultivation and in the production of wheat worldwide. However, semi-arid regions do not seem to have benefited as much from the Green Revolution as other rainfed regions. Nitrogen, phosphorus, and potassium (NPK) fertilisers account for the largest amount of chemical fertiliser used in agricultural systems (Tahakik et al., 2024). By supplying nitrogen in the form of ammonium or nitrate, nitrogen fertilisers meet the plant's nitrogen needs for the biosynthesis of amino acids, key nitrogen-containing compounds, protein synthesis, biosynthesis of enzymes, pigments, and many protective molecules (Zayed et al., 2023). Phosphorus plays a very important role in the structure of nucleic acids and cell division. This element plays a role in stimulating rooting, winter hardiness, improving tillering, and accelerating plant maturation (Malhotra et al., 2018). Although potassium is rarely deficient in soils in semi-arid regions due to the richness of the bedrock and low leaching, this does not mean that plants do not need potassium fertilisers. This element plays a key role in osmotic regulation, plant adaptation to adverse conditions and diseases, improved water absorption, and stomatal regulation and leaf movements (Hasanuzzaman et al., 2018). However, it seems that the application of NPK chemical fertilisers in the relatively unsuitable soil conditions of semi-arid regions has not been fully effective, and before that, some of the physical and chemical limitations of the soil must be overcome. In this context, the use of organic fertilisers can be effective. Given the development of the livestock industry, livestock manure is considered a cheap and accessible source of organic fertiliser in these areas. Therefore, some studies have focused on the effect of replacing organic fertilisers with common chemical fertilisers in these areas (Janmohammadi et al., 2016; Geng et al., 2019; Zhihui et al., 2016, Zhao et al., 2017; Wang et al., 2017). Livestock waste-based fertiliser can be an alternative to mineral fertiliser in achieving high yield and improving soil physical and chemical conditions and soil quality (Wang et al., 2017). The use of combined organic-mineral fertilisers can not only reduce the use of chemical fertilisers but also promote the efficiency and sustainability of agricultural ecosystems in the long term (Zhao et al., 2017). Increasing soil organic matter through the application of organic fertilisers can not only improve the water-holding capacity of the soil but also reduce the rate of climate change. The present experiment aimed to investigate the effect of applying different levels of animal manure and different percentages of suggested amounts of NPK fertilisers under optimal irrigation and rainfed conditions in the Hamedan region on the growth and yield of winter wheat.

MATERIAL AND METHODS

Site description

A field trial was conducted in the Damaq-Kalkaboud region in the west of Iran (35.26°N, 48.50°E, elevation 1840 m) to investigate the effects of different amounts of manure and chemical fertilisers on the vegetative growth and yield of winter wheat. According to the Köppen-Geiger climate classification, this region is cold and semi-arid in terms of climate, with winter and spring rains (early and middle months) prevailing. The average maximum temperature during the growing period was 15.9°C, the average minimum temperature was 2.01°C, the total rainfall during the wheat growing period was 284 mm, the average relative humidity was 55%, and the total evaporation from the surface of the evaporation pan A was 825 mm. The soil texture was loamy clay and contained 287 mg kg^{-1} of potassium, 14 mg kg^{-1} of absorbable phosphorus, 0.12% of total nitrogen, 0.49% of organic carbon, and other chemical properties of the soil were: pH 7.54, percentage of neutralising materials 8.49, electrical conductivity 1.38 ds m^{-1}, calcium carbonate 14%, cation exchange capacity 21.2 Cmolc kg^{-1}. Micronutrients such as zinc and iron were 0.43 ppm and 0.79 ppm, respectively.

Setting up the field experiment

The experiment was conducted as a split-split-plot experiment in a randomised complete block design with three replications. In this experiment, the main factor included irrigation management, which included full irrigation during the growing period and rainfed conditions with one supplementary irrigation. Under full irrigation conditions, five irrigations were performed during the post-sowing, one month after sowing, tillering (emergence of side shoots), booting, and seed-filling stages to a depth of 100 mm. Under dryland conditions, plants grew without irrigation and relied on rainfall, and only one irrigation was performed during the booting stage to a depth of 120 mm. The secondary factor in this experiment was the application of different levels (0, 5, and 10 t ha^{-1}) of animal manure obtained from a calf-rearing farm. The sub-sub-factor included different doses of NPK chemical fertilisers (CH0 – no use of NPK fertiliser, CH50 – application of 50% of the recommended dose of NPK, CH100 – application of 100% of the recommended dose of NPK). Some of the chemical properties of the manure were: pH 7.5, organic carbon percentage 69.48%, electrical conductivity 5.72 dS/m, zinc content 215 ppm, iron 129 ppm, manganese 82 ppm, sulphur content 0.59%, magnesium

0.61%, calcium 1.36%, nitrogen 2.61%, phosphorus 1.05%, and potassium 3.16%. Pishgam winter wheat variety was used for planting. This variety is relatively tolerant to cold and drought stresses, resistant to rust diseases, especially yellow rust. Plant height can reach to 1 m under well irrigated conditions. Its stem is relatively strong and has acceptable tiller production capacity, and with low seed shattering. Its spike is white, with large, light-coloured grains and has a high percentage of grain protein (13%), with strong gluten elasticity, and a high gluten index. Winter Pishgam cv. has a good quality for baking. This cultivar is one of the high-yielding advanced wheat varieties for Iran semi-arid regions. Before planting, the studied area was ploughed in September and divided into main plots (irrigation) and subplots (manure levels). Specified amounts of manure were spread on the surface of the land and incorporated into the soil with a cultivator to a depth of 10 cm. Planting was done manually in early October. The size of each sub-plot was 16 m^2 (4 × 4). Planting was done in rows with 10 cm spacing, and plant density was 300 plants m^{-2}. The recommended amounts of nitrogen, phosphorus, and potassium were 140, 80, and 40 kg ha^{-1}, respectively, which were supplied through urea, triple superphosphate, and potassium sulphate fertilisers. All calculated amounts for phosphorus and potassium fertilisers and one-third of the total nitrogen were applied as a band at planting. The remaining nitrogen fertiliser was used during the stem elongation and booting stages. Between the main plots related to irrigation levels, a distance of one meter was considered as no-planting to prevent moisture leakage and impact on adjacent plots. Irrigation was carried out surface-wise, with water being transferred to the experimental plots through polyethylene pipes. The pipes were equipped with water volume meters.

Measuring agronomic traits

The width or extent of the canopy during the anthesis stage was measured by measuring the extent of leaf and cane development from left to right. The chlorophyll content of flag leaves was measured at the anthesis stage using a SPAD 502 manual chlorophyll meter. At the physiological maturity stage, plant height, peduncle length, and penultimate internode length were measured from the ground level to the highest point of the plant. Quadrat sampling methods were used to evaluate grain yield components. A one-square-metre quadrat was randomly selected. Plants within the quadrat were harvested from the ground, and after counting the number of spikes, the plants were placed in an oven at 72°C for 48 h, and plant biomass was weighed. Then, by grinding the spikes and separating the straw and chaff from the grains, grain yield and thousand-grain weight were measured.

Statistical analysis

Before statistical analysis, a data normality test was performed, and statistical analysis was performed through SAS software. The least significant difference test was used to compare the means. Box plots were drawn through SPSS Statistics. Component analysis (PCA), and clustering of genotypes were executed by Genstat software.

RESULTS

The evaluation of the main effects of irrigation regime (I), animal manure (FYM), and NPK fertilisers (CH) on the vegetative and morphological growth characteristics of wheat is shown in Table 1. The examination of canopy width showed that the interaction effects of I × FYM × CH were significant at the one percent statistical level. The means comparison of the interaction effects (I × FYM × CH) indicated that the highest canopy width (28.33) was achieved with the application of 10 t ha^{-1} of animal manure and 100% recommended doses of chemical fertilisers under full irrigation conditions.

Plants grown under FI + FYM_0 + CH_{100} (27.05 cm) conditions were in second place (Table 2). Applying deficit irrigation conditions reduced canopy width by 8% compared to full irrigation. The application of FYM_5 did not have a significant effect on the canopy width compared to FYM_0. However, application of FYM_{10}

Table 1. **The main effect of the application of different levels of animal manure and NPK chemical fertiliser under different irrigation conditions on vegetative growth characteristics of winter wheat in the Kal-Kaboud region of Hamedan in the west of Iran**

Irrigation	CS	PH	PE	PI	TL	FLC	BI
FI	14.73a	77.62a	18.63a	10.04a	1.92a	59.07a	11556.05a
SI	13.52b	60.72b	11.04b	8.67b	1.41b	39.57b	7266.78b
Animal manure							
FYM_0	18.95b	74.47a	12.74c	8.08b	1.38c	46.08bc	9090.34b
FYM_5	18.28b	68.50b	14.65b	8.55b	1.67b	49.65b	9154.98b
FYM_{10}	20.19a	64.54c	17.12a	11.44a	1.95a	52.24a	9988.9a
Chemical NPK							
CH_0	17.85c	65.60c	13.32c	8.95b	1.76a	48.19b	9109.34c
CH_{50}	19.44b	70.23b	16.30a	8.93b	1.66b	49.67a	9442.51b
CH_{100}	20.08a	71.68a	14.89b	10.18a	1.57c	50.11a	9682.339a
F value in ANOVA							
I	0.002	0.0023	0.0023	0.0025	0.0033	<0.0001	<0.0001
FYM	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
I × FYM	0.061	0.0036	0.1047	0.037	0.076	0.0004	0.116
CH	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0003	<0.0001
I × CH	<0.0001	0.0043	<0.0001	0.157	0.16	0.0025	<0.0001
FYM × CH	<0.0001	0.0001	<0.0001	0.138	0.009	0.001	<0.0001
I × FYM × CH	<0.0001	0.18	0.026	0.0002	<0.0001	0.11	<0.0001
CV%	4.14	2.61	7.38	7.82	6.36	2.62	9.35

FI – full irrigation, SI – supplemental irrigation during the booting stage, FYM_0, FYM_5, and FYM_{10} – application of 0, 5, and 10 t ha^{-1} animal manure, CH_0 – no use of NPK fertiliser, CH_{50} – application of 50% of the recommended dose of NPK, CH_{100} – application of 100% of the recommended dose of NPK. CS – canopy spread (cm), PH – plant height (cm), PE – peduncle length (cm), PI – penultimate internode length (cm), TL – tiller number, FLC – chlorophyll content in flag leaf (SPAD unit), BI – biomass of plant (kg ha^{-1}). At the significance level, *F* values less than 0.05 ($p < 0.05$) and 0.01 ($p < 0.01$) are significant at 95% and 99%, respectively. The means with various letters in each trait (column) are statistically different.

increased the canopy width by 6%. The means comparison of the canopy width at different levels of chemical fertilisers showed that the application of CH_{50} and CH_{100} increased the canopy width by 9% and 14%, respectively. The lowest canopy width was recorded under the conditions of SI + FYM_5 + CH_0 (10.83 cm). Plant height was also significantly affected by the treatments studied. The tallest plants were recorded under FI + FYM_{10} + CH_{50} conditions (81.40 cm), the shortest plants were recorded under SI + FYM_0 + CH_0 conditions (53.71 cm), and SI + FYM_0 + CH_{50} conditions. Under SI conditions, the application of FYM_{10} had a significant effect on plant height.

Evaluation of the length of the upper internodes in the stem, which play a key role in storing surplus photoassimilates, showed that the length of the peduncle (PE) influenced by treatments (I × FYM × CH) at the 5% level significantly, and the effect of treatment on length of the penultimate internode (PI) was statistically significant at the 1% level. The highest PE was obtained in plants grown under FI + FYM_{10} + CH_{50} (24.74 cm), and the highest PI was obtained with FYM_{10} application

Table 2. **The mean comparison of vegetative growth characteristics of winter wheat grown with different doses of chemical fertiliser and farmyard manure under full and supplemental irrigation in the Kal-Kaboud region of Hamedan in the west of Iran**

Combined treatment	CS	PH	PE	PI	TL	FLC	BI
FI + FYM_0 + CH_0	21.59e	70.06gh	17.87cd	7.93ghij	1.83c	51.74f	10510.0g
FI + FYM_0 + CH_{50}	23.52d	77.66cd	16.49def	7.14ij	1.47efg	54.91e	11095.9f
FI + FYM_0 + CH_{100}	27.05ab	74.66de	15.12f	10.22cde	1.48efg	57.53d	12115.6bc
FI + FYM_5 + CH_0	21.56e	73.26ef	17.41de	8.54fgh	2.21b	59.67c	10552.0g
FI + FYM_5 + CH_{50}	25.46c	79.15bc	21.99b	9.04efg	1.85c	58.81cd	11343.8e
FI + FYM_5 + CH_{100}	25.61c	78.93bc	17.87cd	11.12bc	1.73cd	59.18cd	11865.3d
FI + FYM_{10} + CH_0	23.14d	74.97de	16.49def	12.00ab	2.07b	62.10b	11948.5cd
FI + FYM_{10} + CH_{50}	26.31bc	81.39b	24.74a	12.30ab	2.51a	62.25b	12185.8ab
FI + FYM_{10} + CH_{100}	28.33ab	88.50a	19.70c	12.11ab	2.15b	65.51a	12387.5a
SI + FYM_0 + CH_0	16.54fg	53.87l	8.48h	7.70i	1.20hi	35.70k	7045.1ijk
SI + FYM_0 + CH_{50}	12.00jk	55.237l	8.80h	7.26ij	1.19hi	37.50jk	6995.0jkl
SI + FYM_0 + CH_{100}	12.65ij	55.783kl	9.71gh	8.27fghi	1.12i	39.13jhi	6780.5l
SI + FYM_5 + CH_0	10.83K	58.42jk	8.48h	8.12ghij	1.48efg	40.90hi	6865.9kl
SI + FYM_5 + CH_{50}	14.01gh	60.12ij	11.09g	7.47i	1.40fg	41.17h	7092.0ij
SI + FYM_5 + CH_{100}	12.24ij	61.123ij	11.09g	7.03j	1.36gh	38.20j	7210.8i
SI + FYM_{10} + CH_0	13.45hi	63.03i	11.23g	9.47def	1.82c	39.03ij	7734.5h
SI + FYM_{10} + CH_{50}	15.33fg	67.86h	14.71f	10.41cd	1.57def	43.43g	7942.5h
SI + FYM_{10} + CH_{100}	14.61gh	71.1fg	15.85f	12.36a	1.60de	41.13hi	7734.8h

FI – full irrigation, SI – supplemental irrigation during the booting stage, FYM_0, FYM_5, and FYM_{10} – application of 0, 5, and 10 t ha^{-1} animal manure, CH_0 – no use of NPK fertiliser, CH_{50} – application of 50% of the recommended dose of NPK, CH_{100} – application of 100% of the recommended dose of NPK. CS – canopy spread (cm), PH – plant height (cm), PE – peduncle length (cm), PI – penultimate internode length (cm), TL – tiller number, FLC – chlorophyll content in flag leaf (SPAD unit), BI – biomass of plant (kg ha^{-1}). The means with various letters in each trait (column) are statistically different.

under full irrigation conditions. Comparison of PI between FYM levels showed that no significant difference was observed between FYM_5 and FYM_{10}. However, the application of 5 and 10 t ha^{-1} of FYM increased peduncle length by 15% and 34% compared to the control. The evaluation of the effect of chemical fertilisers on peduncle length showed that the application of CH_{50} had the greatest increasing effect on this component, while the application of CH_{100} resulted in the highest PI value (Table 2).

Reducing irrigation frequency (SI) reduced tiller number per plant by about 26% compared to full irrigation. Application of 5 and 10 t ha^{-1} FYM increased tiller number by 21% and 41% compared to FYM_0. The mean comparison of tiller number between chemical fertiliser levels showed that the application of CH_{50} had the greatest effect on improving this component. The lowest tiller number was recorded under SI + FYM_0 +CH_{100} conditions (1.12) and the highest tiller number was related to plants grown under FI + FYM_{10} + CH_{50} conditions (2.51).

Chlorophyll evaluation showed that the interactions of I × CH, I × FYM, and FYM × CH were significant. Comparison of the mean interactions of FYM × CH showed that the highest chlorophyll content was recorded in plants grown with FYM_{10} + CH_{100} (53.32) and FYM_{10} + CH_{50} (52.84). The lowest chlorophyll content was observed under FYM_0 + CH_0 conditions. Evaluation of the means for the interaction of I × CH indicated that the highest chlorophyll content of flag leaves was recorded in plants grown under FI + CH_{100} conditions (60.74) and the lowest under SI + CH_0 conditions (38.54). Evaluation of the means for the interaction of I × FYM showed that the highest chlorophyll content was recorded under FI + FYM_{10} conditions (63.28) and the lowest was observed under SI + FYM_0 conditions.

Water shortage caused a 38% reduction in plant biomass compared to fully irrigated conditions. The use of FYM_5 and $FMYM_{10}$ resulted in a 7% and 10% increase in biomass compared to FYM_0. The highest plant biomass was recorded under FI + FYM_{10} + CH_{100} conditions (12387 kg ha^{-1}) and the lowest biomass was recorded for the plants grown under SI + FYM_0 + CH_0 conditions (6780 kg ha^{-1}). Spike length was also affected by the treatments studied (Table 3). Reducing moisture content

Table 3. **Evaluation of the main effects of the application of different doses of NPK fertilisers and animal manure under conditions of full irrigation and supplementary irrigation on winter wheat yield components in the western region of Iran**

Irrigation	SL	SW	SN	WTG	GY	HI	GP
FI	12.25a	726.94a	402.49a	42.64a	4063.81a	35.16a	10.51b
SI	9.17b	513.46b	309.59b	37.67b	2221.11b	30.47b	11.58a
Animal manure							
FYM_0	10.41c	605.78b	341.56c	40.16ab	2808.6c	30.14b	10.83c
FYM_5	10.83b	606.91b	358.81b	39.96b	3157.7b	34.04a	11.03b
FYM_{10}	11.15a	664.24a	367.74a	40.33a	3461.02a	34.26a	11.28a
Chemical NPK							
CH_0	10.49b	602.34b	337.23c	40.51a	3009.16	32.62a	10.82c
CH_{50}	10.85a	634.09a	360.78b	40.21b	3192.60a	33.26a	11.09b
CH_{100}	10.87a	639.17a	370.10a	39.74c	3225.60a	32.56a	11.24a
F value in ANOVA							
I	0.0007	<0.0001	<0.0001	0.0002	0.0003	0.0095	<0.0001
FYM	<0.0001	<0.0001	<0.0001	0.0497	<0.0001	<0.0001	<0.0001
I × FYM	0.001	<0.0001	0.0003	0.0006	0.024	<0.0001	<0.0001
CH	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.095	<0.0001
I × CH	<0.0001	<0.0001	0.0013	0.286	<0.0001	0.131	0.0004
FYM × CH	0.0005	0.0007	0.076	<0.0001	0.0001	0.0006	0.0016
I × FYM × CH	0.0003	0.0174	0.062	0.069	<0.0001	<0.0001	<0.0001
CV%	1.78	1.57	3.01	1.24	7.14	7.09	1.06

FI – full irrigation, SI – supplemental irrigation during the booting stage, FYM_0, FYM_5, and FYM_{10} – application of 0, 5, and 10 t ha^{-1} animal manure, CH_0 – no use of NPK fertiliser, CH_{50} – application of 50% of the recommended dose of NPK, CH_{100} – application of 100% of the recommended dose of NPK. SL – spike length (cm), SW – spike weight per m^2 (g), SN – spike number per m^2, WTG – thousand-grain weight (g), GY – grain yield (kg ha^{-1}), HI – harvest index (%), GP – grain protein percentage (%). At the significance level, *F* values less than 0.05 ($p < 0.05$) and 0.01 ($p < 0.01$) are significant at 95% and 99%, respectively. The means with various letters in each trait (column) are statistically different.

in SI conditions reduced spike length by 25% compared to full irrigation conditions. Application of FYM_5 and FYM_{10} increased spike length by 4% and 7% compared to control conditions. The longest spikes were observed under FI + FYM_{10} + CH_{100} conditions (12.87 cm) and the shortest spikes were observed under SI + FYM_0 + CH_{100} conditions (8.10 cm).

The number of spikes per square metre decreased by 23% under SI conditions with reduced irrigation frequency compared to full irrigation conditions. The use of 5 and 10 t ha^{-1} of animal manure increased the number of spikes per unit area by 6% and 8%, respectively, compared to the control (Table 3). However, the application of CH_{50} and CH_{100} increased the number of spikes by 7% and 10% compared to the control. The highest number of spikes per unit area was recorded in the FI + FYM10 + CH100 condition (441.77) and the lowest observed (256.67) in the SI + FYM0 + CH0 condition (Table 4). The lowest grain weight (WTG) was recorded under SI conditions. Reducing irrigation frequency under SA conditions reduced WTG by 12% compared to full irrigation.

Comparison of mean WTG for FYM × CH interactions indicated that the highest 1000-grain weight was recorded in plants grown under FYM_{10} + CH_0 (41.29 g) and the lowest 1000-grain weight was recorded under

Table 4. **The mean comparison of vegetative growth characteristics of winter wheat grown with different doses of chemical fertiliser and farmyard manure under full and supplemental irrigation in the Kal-Kaboud region of Hamedan in the west of Iran**

Combined treatment	SL	SW	SN	WTG	GY	HI	GP
FI + FYM_0 + CH_0	11.26e	677.59h	377.56f	43.59a	3628f	34.52cde	10.28h
FI + FYM_0 + CH_{50}	11.41e	696.58fg	396.97cde	43.29a	3781.33e	34.09def	10.43gh
FI + FYM_0 + CH_{100}	12.00d	723.17de	420.87b	42.25bc	3864de	31.9g	10.84e
FI + FYM_5 + CH_0	12.18cd	680.35gh	379.43ef	41.63c	3890.33de	36.87b	10.42gh
FI + FYM_5 + CH_{50}	12.56ab	706.94ef	401.83cd	42.59b	4087.33c	36.0333bc	10.36h
FI + FYM_5 + CH_{100}	12.87a	731.11d	412.65bc	41.92bc	4196c	35.3767bcd	10.61fg
FI + FYM_{10} + CH_0	12.40bc	749.76c	385.77def	43.59a	3911.33d	32.73fg	10.37h
FI + FYM_{10} + CH_{50}	12.69ab	812.60b	405.56bc	42.59b	4425.67b	36.3167b	10.59fg
FI + FYM_{10} + CH_{100}	12.87a	854.39a	441.77a	42.33b	4790.32a	38.6767a	10.78ef
SI + FYM_0 + CH_0	9.02ij	499.32lm	256.67k	37.45gf	1861.5jk	26.44hi	11.16d
SI + FYM_0 + CH_{50}	9.07hij	525.62ij	293.00j	37.14g	1953.86j	27.93h	11.25cd
SI + FYM_0 + CH_{100}	8.10k	513.00jkl	304.33ij	37.27gf	1762.92k	26.00i	11.08d
SI + FYM_5 + CH_0	8.84j	499.32lm	313.33hi	37.85ef	2214.29i	32.2533g	11.26cd
SI + FYM_5 + CH_{50}	9.35gh	524.04ij	328.00gh	38.29e	2263.66i	31.92g	11.76b
SI + FYM_5 + CH_{100}	9.20hi	491.16m	317.67hi	37.55gf	2295.00i	31.84g	11.81b
SI + FYM_{10} + CH_0	9.27hi	507.73kl	310.67hij	38.99d	2549.48gh	32.9667efg	11.43c
SI + FYM_{10} + CH_{50}	10.02f	538.78i	339.33g	37.38gf	2643.97g	33.29efg	12.20a
SI + FYM_{10} + CH_{100}	9.64g	522.20jk	323.33gh	37.14g	2445.33h	31.59g	12.34a

FI – full irrigation, SI – supplemental irrigation during booting stage, FYM_0, FYM_5 and FYM_{10} – application of 0, 5, and 10 t ha^{-1} animal manure, CH_0 – no use of NPK fertiliser, CH_{50} – application of 50% of the recommended dose of NPK, CH_{100} – application of 100% of the recommended dose of NPK. SL – spike length (cm), SW – spike weight per m^2 (g), SN: spike number in spike, WTG: thousand grain weight (g), GY: grain yield (kg ha^{-1}), HI: harvest index (%), GP: grain protein percentage. The means with various letter in each trait (column) are statistically different.

FYM_5 + CH_{100} conditions (39.73 g). The mean comparison of grain yield under different soil moisture conditions showed that reducing irrigation frequency under SI conditions resulted in a 45% reduction compared to full irrigation conditions (Table 3). The use of FYM5 and FYM10 increased grain yield by 12% and 23% compared to the control. The use of NPK fertilisers at doses of 50% and 100% increased yield by 6% and 8%, respectively, compared to conditions without fertiliser use. The triple interaction effects of I × FYM × CH on grain yield were significant. The highest grain yield was recorded under FI + FYM_{10} + CH_{100} conditions (4790.32 kg ha^{-1}) and the lowest grain yield was recorded under SI + FYM_0 + CH_{100} conditions (1762 kg ha^{-1}). The application of chemical fertilisers under FYM_0 and FYM_5 conditions did not have much effect on improving grain yield (Table 4). Even in plants grown under FYM_0, the application of chemical fertilisers reduced grain yield. The means comparison for grain protein percentage showed that by reducing irrigation frequency (SI), the amount of this quality trait increased by about 1%. The use of animal manure also significantly increased the percentage of grain protein compared to the control. The highest protein percentage was recorded in plants grown under supplementary irrigation conditions with high levels of manure and CH_{50} and CH_{100} application with 12.20% and 12.34%, respectively. The lowest grain protein percentage was observed under FI + FYM_0 + CH_0 conditions (10.28%).

Clustering of treatment combinations based on similarity in influencing agronomic and morphological traits evaluated showed that the most important factor for clustering was the irrigation regime and the second determining factor in grouping was the FYM application. The most effective combined treatments under full irrigation conditions were those with high levels of manure along with CH_{50} and CH_{100}. However, statistical classifications placed all combined treatments under full irrigation in cluster 1 (Fig. 1). Under moisture deficit (SI) conditions, there was no significant difference between FYM_0 and FYM_5 applications, and these combinations were placed in cluster 2. The best plant performance under SI conditions was achieved with the application of FYM_{10}, CH_{50}, and CH_{100}, and these combined treatments were in cluster 3.

Clustering of agronomic traits based on behavioural similarity against the treatments studied showed that canopy width, biomass, flag leaf chlorophyll, spike weight, spike length, plant height, number of spikes per unit area, and grain yield were placed in one group (Fig. 2). These traits showed a significant increase with

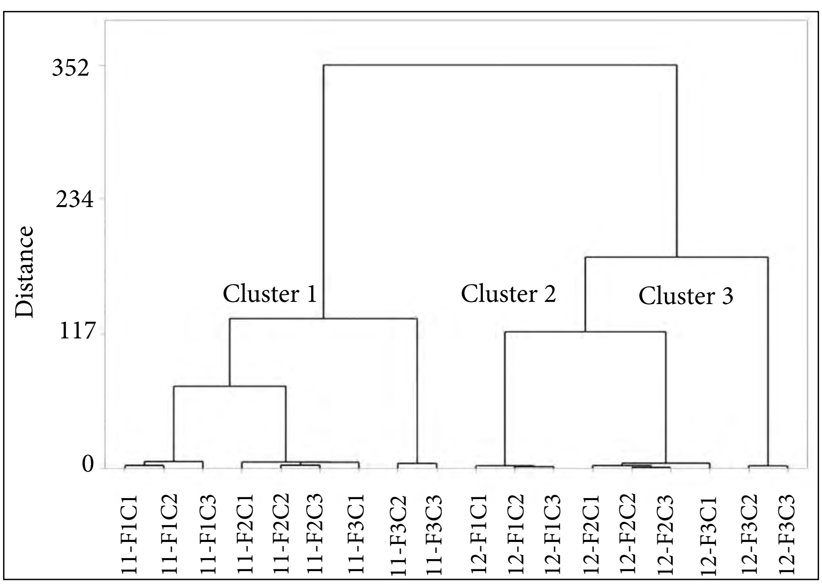

Fig. 1. Grouping of treatment compounds according to similarity in influencing vegetative growth characteristics and yield components of wheat. FI – full irrigation, SI – supplemental irrigation during the booting stage, F1, F2, and F3 – application of 0, 5, and 10 t ha^{-1} animal manure, C_1 – no use of NPK fertiliser, C_2 – application of 50% of the recommended dose of NPK, C_3 – application of 100% of the recommended dose of NPK

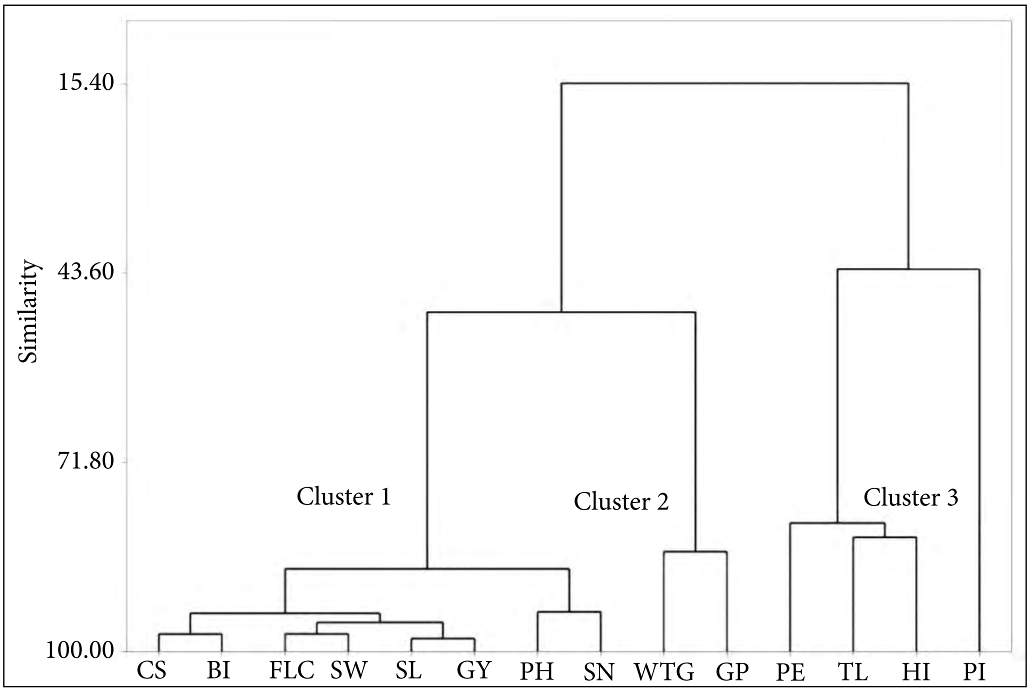

Fig. 2. Grouping of vegetative characteristics and grain yield components according to similarity in influencing vegetative growth characteristics and yield components of wheat of NPK. CS – canopy spread, PH – plant height, PE – peduncle length, PI – penultimate internode length, TL – tiller number, FLC – chlorophyll content in flag leaf, BI – biomass of plant. SL – spike length, SW – spike weight, SN – spike number, WTG – thousand-grain weight, GY – grain yield, HI – harvest index

the application of chemical fertilisers under full irrigation conditions. However, under SI conditions, the application of chemical fertilisers, especially without the use of animal manure, did not have a significant effect on their improvement. Thousand-grain weight and protein percentage were in the second group. These components decreased with increased use of chemical fertilisers, and the percentage of grain protein increased with decreasing irrigation. Traits such as peduncle length, number of tillers, harvest index, and length of the penultimate upper internodes were placed in the third group, and their lowest values were obtained under deficit irrigation conditions and no use of animal manure.

DISCUSSION

Soil conditions in the studied area indicated that nutrient deficiency in the soil was one of the limiting factors for plant growth. Therefore, specific and intelligent climate resilient management that is adapted to climate change seems essential for these regions. The deficiency of soil organic matter in the study area was quite evident, which probably affected and reduced the water holding capacity of the soil. In addition, low organic matter in the soil itself can affect the availability of nutrients through inappropriate pH and the low release of decomposing organic matter. Under such conditions, there will be little available nutrients in the rhizosphere environment. The rainfall during the vegetation period was about 280 mm and the evaporation rate from the evaporation pan was estimated around 800 mm. These results indicate a severe lack of water in the soil for transpiration, and in the absence of irrigation, water deficit stress seems inevitable. Considering the rainfall pattern and climatic conditions in the region, water shortage is likely at the end of the reproductive period, and the use of supplementary irrigation is therefore necessary. It is important to apply a precise irrigation schedule and allocate a portion of the available water for irrigation during the reproductive period. Comparison of plants grown under full irrigation and supplementary irrigation conditions showed that water deficit under rainfed-supplementary irrigation conditions reduced both vegetative and reproductive growth. The findings of the present study showed that applying a single supplementary irrigation with a depth of 120 mm was not sufficient to improve the performance of Pishgam winter wheat and could not meet the economic expectations of the farmer. Most of the precipitation occurs during the cold months of the year, and probably due to the high need for evaporation, a significant portion of the moisture stored in the soil is lost as evaporation without playing a physiological role in the plant. Therefore, for the current conditions, improving water storage in the soil and increasing water supply through irrigation should be on the agenda. One way to increase water storage in soil is to use manure. Researchers have shown that even short-term application of manure improves soil water storage capacity by changing the physical properties of the soil (Nouraein et al., 2019; Janmohammadi et al., 2024a). However, what the results reflect is that in this experiment, due to poor soil conditions, the use of small amounts of manure could not fully improve plant growth by improving soil conditions and increasing reserves. The results showed that the application of rainfed conditions (without irrigation) reduced the vegetative growth of the plant, and this was evident even under the conditions of application of FYM_{10}. The wheat plant depends on two sources of photoassimilation for grain yield and filling the seed cup, namely, the ongoing photosynthesis and the re-transport of photoassimilates stored in temporary reservoirs such as the upper nodes of the stem (Smith et al., 2018). Chlorophyll assessment showed that water deficit under rainfed conditions or lack of chemical and animal fertilisers caused a significant decrease in the photosynthetic pigment content in flag leaves. This decrease can be attributed to a decrease in the durability of the green surface and a decrease in the width of photoassimilates through the ongoing photosynthesis (Aljazairi López et al., 2024; Janmohammadi et al., 2024b). In other words, moisture deficiency and nutrient deficiency during the growth period affected the source-sink relationships in a way. Green leaves as the main photosynthetic tissues or green stems and even green bracts play a role in the production of photoassimilates on an ongoing basis and are considered as sources (Simkin et al., 2020). Low soil moisture through stomatal restriction and reduced gas exchange leads to reduced photosynthesis. Reduced nutrient supply through fertilisers can also disrupt chlorophyll biosynthesis (Urban et al., 2017). The achieved results show that the application of animal manure must be included in the agenda to increase production and stabilise yield in rainfed fields (Zia et al., 2020). Under rainfed conditions, replacing some of the chemical fertilisers with organic fertilisers seems to be essential. Intensification of water deficit and reduction of chlorophyll in the flag leaf can also disrupt the functions of photosynthetic enzymes and impose non-stomatal limitation on photosynthesis. Photoassimilates themselves can also affect the formation or non-appearance of yield potential. It seems that insufficient water content in the soil under rainfed conditions with supplementary irrigation and lack of sufficient photoassimilate supply caused a large number of reproductive primordia not to be converted into yield components. Furthermore, primordia of yield components and seeds are formed early in the stem, which is usually the period of high rainfall in the studied region, but gradually the rainfall decreases and due to the severe decrease in the supply of photoassimilates, primordia cannot be converted into yield components. Under such conditions, even the use of high levels of FYM and chemical fertilisers could not compensate for this deficiency. The use of high levels of chemical fertilisers did not have much effect on improving yield under rainfed conditions. In some cases, the use of high levels of chemical fertilisers even reduced it. It seems that the increased use of chemical fertilisers exacerbated the water shortage for key reproductive stages by stimulating vegetative growth and wasting soil moisture reserves (Hosseinzadeh et al., 2025). The increase in protein percentage under drought stress conditions can be attributed to accelerated leaf senescence, increased leaf protein degradation, and increased nitrogen retransfer from leaves to filling seeds (Hajibarat, Saidi, 2022). The results showed that the use of FYM_{10} is necessary for both full irrigation and rainfed conditions, but in rainfed conditions, the use of chemical fertilisers should be reconsidered. The gradual application of fertilisers when providing moisture during the wet season can possibly be a solution for this problem (Shanmugavel et al., 2023). The results of the present experiment show that the studied treatments had a significant effect on the distribution of substances between reproductive and vegetative organs and, consequently, on the harvest index. Water supply and application of FYM_{10} under full irrigation conditions significantly increased the harvest index. Application of FYM_{10} + CH_{50} under rainfed conditions also partially improved the harvest index. Our findings confirmed the results of Wang et al. (2021). Under rainfed conditions, increasing the use of chemical fertilisers will not necessarily increase yield. Before increasing the use of chemical fertilisers, the physical, chemical, and biological conditions of the soil should be improved through available organic amendments such as animal manure.

CONCLUSIONS

The present experiment showed that comparing the effects of irrigation treatments and the application of chemical or organic fertilisers, plants showed more intense and significant responses to irrigation treatments. Water management is more important than nutrient management in wheat production systems in the mentioned region. The results showed that one irrigation at the booting stage was not very effective and efficient in increasing wheat production, and more frequent supplementary irrigation is probably needed. Under full irrigation conditions, the application of chemical fertilisers had a significant effect on improving grain yield and the role of these fertilisers in increasing production cannot be ignored. Under rainfed conditions with supplementary irrigation, the application of 50% of the recommended doses of chemical fertilisers along with the application of 10 t ha^{-1} of animal manure had a greater effect on improving wheat grain growth and yield.

Conflict of interest: The authors have no conflicts of interest to declare.

Ethics committee approval: The data from this experiment does not conflict with ethical principles and is irrelevant in this regard.

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CHEMINIŲ TRĄŠŲ IR GYVULIŲ MĖŠLO POVEIKIS KVIEČIAMS SKIRTINGOMIS DIRVOŽEMIO DRĖGMĖS SĄLYGOMIS

Santrauka

Dėl stiprėjančių klimato kaitos padarinių, būtinybės taikyti klimatui atsparius metodus bei gerinti mitybos sąlygas, pusiau sausringuose regionuose vis dažniau svarstoma apie cheminių trąšų pakeitimą organinėmis ir mažesnį vandens sunaudojimą. Lauko eksperimentu siekta įvertinti NPK cheminių trąšų skirtingų normų (CH_0 – nenaudojamos NPK trąšos, CH_{50} – 50 % NPK norma, CH_{100} – 100 % NPK norma) ir gyvulių mėšlo įvairaus kiekio (0, 5 ir 10 t ha^{-1} – atitinkamai FYM_0, FYM_5 ir FYM_{10}) poveikį žieminių kviečių (*Triticum aestivum*) augimui skirtingomis dirvožemio drėgmės sąlygomis (giluminis laistymas – FI ir nedrėkinimas su vienu papildomu laistymu varpos formavimosi tarpsniu – SI) Hamedano regione. FI sąlygomis cheminių trąšų naudojimas žymiai pagerino šoninį augimą (lapijos tankį), o augimas į ilgį ir ūglių ilgis buvo didesnis derinant chemines ir organines trąšas. SI sąlygomis didžiausią poveikį derliui turėjo FYM_{10}+CH_{50} derinys. Grūdų masė mažėjo esant abiem drėkinimo režimams ir didinant NPK trąšų normą. Didžiausias grūdų derlius (4 790 kg ha^{-1}) buvo gautas taikant FI+FYM_{10}+CH_{100} tręšimo variantą, antroje vietoje – FYM_{10}+CH_{50} (4 425 kg ha^{-1}) tręšimas. SI sąlygomis didžiausias derlius buvo užfiksuotas naudojant FYM_{10}+CH_{50} (2 644 kg ha^{-1}) ir FYM_{10}+CH_{0} (2 549 kg ha^{-1}) tręšimą, o mažiausias – be mėšlo (FYM_{0}). Siekiant didesnio grūdų derliaus FI sąlygomis, cheminių trąšų naudojimas yra neišvengiamas, nes reikšmingai didesniam derliui dabar naudojamo mėšlo kiekio nepakanka.

Reikšminiai žodžiai: giluminis drėkinimas, organinės trąšos, varpos ilgis, ūglių skaičius, *Triticum aestivum*, vegetatyvinis augimas, stresas dėl vandens trūkumo