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Original Research

Interactive Effects of Irrigation Methods and Fertilization Gradients on Winter Wheat Growth and Yield

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Abstract

Field water and fertilizer management are closely related to wheat growth, and a reasonable water and fertilizer pattern is helpful in increasing wheat production. In order to investigate the changes in growth and yield of wheat under different fertilization gradients and water conditions, a field experiment was conducted in Zhengzhou, China (2022–2023), using two irrigation treatments – sufficient (C) and insufficient (M), and five fertilizer regimes (N=180 kg/ha): organic fertilizer alone (L1), organic-inorganic ratios of 7:3 (L2) and 3:7 (L3), chemical fertilizer alone (L4), and no fertilizer (L5). Results indicated that insufficient irrigation (M) significantly enhanced wheat physiological growth under fertilized conditions, whereas the sufficient irrigation (C) treatment showed better growth without fertilization. Insufficient irrigation combined with a high organic fertilizer ratio notably improved yield, yet the highest yield (10,485.51 kg/ha) was achieved with chemical fertilizer alone (L4). Yield exhibited a strong positive correlation ($p<0.01$) with plant height, leaf area index (LAI), relative chlorophyll content (SPAD), transpiration rate (Tr), photosynthetic rate (Pn), and stomatal conductance (Gs). Short-term experimental findings suggest that insufficient irrigation with high or exclusive chemical fertilizer application optimizes winter wheat growth and productivity. These results provide valuable insights into designing field water-fertilizer strategies to maximize wheat yield.

Keywords: insufficient irrigation, fertilizer ratio, physiological growth, yield, regression analysis

Introduction

About 200 million hectares of cropland are dedicated to wheat production, which is essential to the world's food security. Global wheat demand is expected to rise by 1.7% per year by the middle of the 21st century, but wheat production is probably only going to rise by 1.1% annually. Enhancing soil and water management techniques has been demonstrated in studies to help boost agricultural yields [1-3]. In dry regions of China, water-saving agriculture is a crucial means of achieving sustainable agricultural development. Water status can influence crop development and physiological processes, as well as material and photosynthetic product transport, thereby impacting nutritional and reproductive growth, and ultimately determining yield formation. Research has indicated that the amount of irrigation water has a notable impact on the height of plants, the amount

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of dry matter present above ground, the area of leaves, and the quality of wheat grains. The average wheat plant height increased steadily as irrigation volume increased. Dry matter mass in the aboveground part, leaf area, and spike grain mass all exhibited an increasing and then decreasing trend. Additionally, the photosynthetic rate (Pn), transpiration rate (Tr), and foliar stomatal conductance (Gs) all increased as irrigation volume increased. However, excessive irrigation decreased the net photosynthetic rate [4]. As a key factor in improving crop yield, nitrogen fertilizer can effectively promote dry matter mass and nitrogen accumulation of wheat with reasonable application of nitrogen fertilizer [5, 6], but excessive application of nitrogen impairs the growth of wheat [7]. In the study by Li et al. [8], wheat growth was optimized at N135 (nitrogen application of 135 $kg \cdot hm^{-2}$), and growth status was better in terms of SLA (specific leaf area), LW (leaf weight), and LL (leaf length) than under the N180 (nitrogen application of 180 $kg \cdot hm^{-2}$) treatment. This suggests that applying too much nitrogen fertilizer is harmful to wheat growth. Additionally, nitrogen is essential for the production of chlorophyll, which has an impact on plant photosynthesis. Under the same circumstances, wheat leaves displayed an increasing trend in Tr, Pn, and Gs, and the chlorophyll and soluble protein content of wheat also increased with the increasing amount of nitrogen fertilizer [9]. Studies have demonstrated that the application of organic fertilizers can enhance fertilizer efficiency, mitigate nitrogen, phosphorus, and potassium loss [10], and foster crop development by augmenting soil nutrient levels and fertilizer availability, thereby achieving elevated crop yields and productivity [11]. Zhang et al. [12] discovered that substituting chemical fertilizers with organic ones in suitable proportions can decelerate the decline of wheat leaves, augment photosynthetic activity, thereby promoting wheat plant and grain development, and ultimately leading to an increase in spike numbers and thousand-grain weight. Moreover, Li et al. [13] found that organic fertilizer application significantly boosts soil fertility, enhances chlorophyll formation in crops, improves wheat flag leaf photosynthetic attributes, stimulates photosynthesis [14, 15], augments dry matter content, and accumulates dry matter, consequently elevating wheat yields. To investigate the impact of different irrigation volumes and fertilization gradients on wheat's physiological growth indicators and yield, this study employed a field plot to analyze the effects of five distinct fertilizer ratios combined with two irrigation conditions, aiming to determine the optimal water-fertilizer combination under wheat's optimal growth conditions. Additionally, it conducted a comprehensive assessment of field water and fertilizer management strategies to enhance wheat yield.

Materials and Methods

Experimental Site

The experiment was conducted from October 2022 to June 2023 at the Experimental Site for Efficient Water Use in Agriculture, located at the Longzi Lake Campus of North China University of Water Resources and Hydropower in Zhengzhou, Henan Province (Fig. 1). Photos taken at the beginning and end of the experiment are also shown in Fig. 1. The site is located within the Central China Plain at coordinates 34.78°N, 113.76°E, with an elevation of 110 m. The prevailing climate is warm temperate continental monsoon, characterized by an average annual temperature of 14.5ºC, an average annual precipitation of 637.1 mm, a daily average sunshine duration of 6.57 hours, and a frost-free period spanning 220 days. The terrain is predominantly flat, featuring a topsoil composed of clay loam. In the 0~60 cm soil layer, the average soil mass fractions of organic matter, available potassium, available phosphorus, total nitrogen, and alkaline dissolved nitrogen were measured at 870 mg/kg, 104.4 mg/kg, 11.8 mg/kg, 539 mg/kg, and 45~60 mg/kg, respectively. The primary physical and chemical properties of the 0~60 cm soil layer are summarized in Table 1.

Fig. 1. Location of the test area.

Table 1. Properties of test soils.

Soil depth (cm)	Physical and Chemical Parameters								Particle Size Composition (%)		
	Bulk Mass (g/cm^3)	Field Capacity (cm^3/cm^3)	Organic Substance (g/kg)	Total Nitrogen (g/kg)	Total Phosphorus (g/kg)	Total Potassium g/kg)	Nitrate Nitrogen (mg/kg)	Ammonium Nitrogen (mg/kg)	Grit	Soil Grain	Agglomerate
0~20	1.35	32	9.16	0.566	0.2420	0.0227	11.723	0.24	0.17	0.64	0.19
20~40	1.56	34	6.67	0.364	0.2495	0.0230	11.006	0.229	0.11	0.65	0.24
40~60	1.41	34	2.79	0.195	0.2236	0.0212	10.332	0.214	0.09	0.65	0.26

Experimental Design

The field experiment was conducted under uniform conditions, employing the same winter wheat varieties and basal soil fertility. It was designed to incorporate two irrigation methods and five fertilization gradients. The irrigation methods included sufficient irrigation (C) and insufficient irrigation (M), with water application rates of 750 m^3/hm^2 and 450 m^3/hm^2, respectively, during the growth stages of wheat. Conventional sufficient irrigation was carried out at three key stages: the overwintering stage (December 8, 2022), the regreening stage (March 3, 2023), and the jointing stage (March 30, 2023). Five fertilization treatments were implemented, ensuring consistent nitrogen (N) application at 180 kg/hm^2 [16]. These treatments comprised single applications of organic fertilizers, organic-inorganic fertilizers at ratios of 7:3 and 3:7, and a control group with no fertilizer applied. The treatments were labeled as L1, L2, L3, L4, and L5, representing a total of 10 treatment plots. Each experimental plot occupied an area of 28 m^2 (4 m width × 7 m length), with a 1-meter spacing between adjacent plots (refer to Fig. 2). Winter wheat was sown manually on October 11, 2022, with approximately 0.3 m of spacing between rows. It was strip-seeded at a depth of 0.05 meters below the ground using a self-propelled planter, at a seeding rate of 320 kg/hm^2. Harvesting took place on June 1, 2023.

Materials for Testing

The winter wheat variety utilized in this experiment is Jimai 22, a variety developed through hybridization by the Crop Research Institute of the Shandong Academy of Agricultural Sciences. Jimai 22 is classified as a semi-winter variety, exhibiting medium-late maturity, with a growth cycle spanning 239 days. It boasts commendable resistance to various diseases. For basal fertilization, a single application was carried out prior to sowing, utilizing compound fertilizer manufactured by Jiangxi Open Door Fertilizer Limited Liability Company. The compound fertilizer contains a minimum of 41% total nutrients, with a nutrient ratio of $N:P_2O_5:K_2O$ = 17:17:7. Organic fertilizers were sourced from the Beijing Academy of Agricultural Sciences Biological Research Institute, offering highly active organic fertilizers with an organic matter content of at least 60%. Nitrogen, phosphorus, and potassium contents in the organic fertilizers are all ≥6%. These organic fertilizers comprise potassium xanthate, humic acid, amino acids, trace elements, and beneficial active bacteria with a content of ≥0.5 billion/g. Follow-up fertilization was conducted on March 30, 2023, with a base-to-top dressing ratio of 6:4 for each treatment. The specific quantities of irrigation water and fertilizer applied to each treatment are detailed in Table 2. Throughout the growth stages of winter wheat, consistent agronomic practices such as hoeing and pest control were

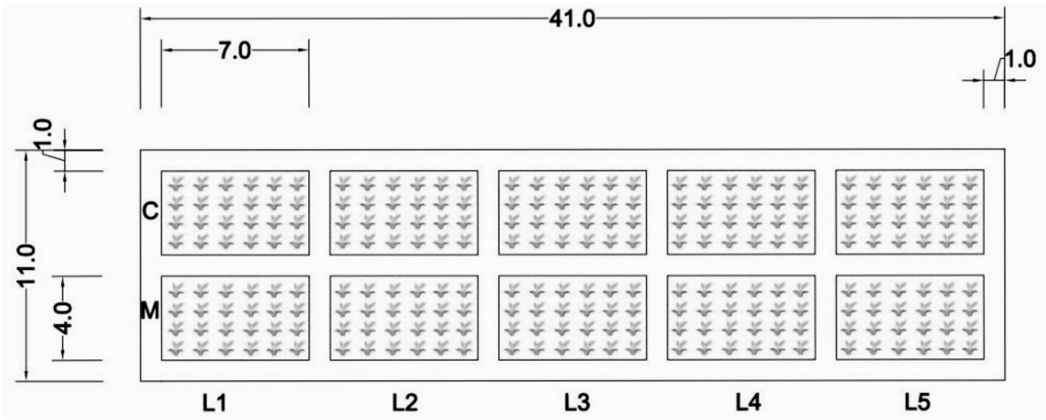

Fig. 2. Design of the experimental field (Unit: m).

Table 2. Total amount of irrigation and fertilizer applied to each experimental plot.

Treatment	Compound fertilizer			Highly active organic fertilizer			Irrigation amount mm
	N (kg/hm^2)	P_2O_5 (kg/hm^2)	K_2O (kg/hm^2)	N (kg/hm^2)	P_2O_5 (kg/hm^2)	K_2O (kg/hm^2)	
L1C	0	0	0	180	180	180	75
L2C	54	54	22.5	126	126	126	75
L3C	126	126	52	54	54	54	75
L4C	180	180	74	0	0	0	75
L5C	0	0	0	0	0	0	75
L1M	0	0	0	180	180	180	45
L2M	54	54	22.5	126	126	126	45
L3M	126	126	52	54	54	54	45
L4M	180	180	74	0	0	0	45
L5M	0	0	0	0	0	0	45

implemented. Pest control measures were administered by the local agricultural station, targeting pests such as aphids and cutworms.

Indicators and Methods

Measurement of Population Dynamics

Plant height and root length: Five representative winter wheat plants were selected from each experimental plot, and a steel tape measure was used to measure plant height. After the filling stage, the height was measured from the base of the plant to the top of the spike (excluding the awns), and the root length was the longest length of the roots taken.

Leaf area index (LAI): Five representative winter wheat single-stemmed plants were selected from each experimental plot, and a YMJ-B hand-held leaf area meter was used to measure the leaf area of the flag leaf and inverted biloba of the plants, and the leaf area index was calculated using the following formula [17]:

$$LAI = \rho \frac{\sum_{i=1}^{m} S_i}{m} \tag{1}$$

In the formula, *LAI* is the leaf area index; ρ is the planting density (plants/m²); *m* is the total number of leaves per plant; and *Si* is the leaf area of a single plant (mm²).

SPAD content: Five representative single-stem winter wheat plants were selected from each experimental plot, and the relative chlorophyll content of the flag and second leaves of the plants was measured using the SPAD-502 chlorophyll content analyzer.

Measurement of Photosynthetic Indexes

In sunny and windless weather, the photosynthesis rate was measured using a portable photosynthesis-fluorescence measurement system GFS-3000 to determine the changes in net photosynthetic rate (Pn), transpiration rate (Tr), and stomatal conductance (Gs) of winter wheat leaves under different treatment conditions. The sampling time of each group of data was about 1 minute, and the results were stored automatically. Measurements were taken once in each fertility period, from 9:00 to 11:00, on five randomly selected plants. The measurement was conducted on the inverted two-leaf, with the measurement point located in the middle of the leaf.

Yield and Seed Copying

Wheat was harvested on June 1, 2023, and three sample squares were selected from each experimental plot, each covering an area of 1 m² for yield measurement. The harvested kernels were used to determine their fresh weight, the number of grains per spike, and the number of spikes. The samples were then dried, weighed, converted to hectare yield, and used to calculate the moisture content of the crop. Five plants were randomly selected from each sample square, and the stems, leaves, and spikes of the winter wheat plants were dried to measure aboveground dry matter, dry weight of kernels, and 1,000-kernel weight, and to calculate the harvest index using the following formula:

$$HI = \frac{Y}{B} \tag{2}$$

In the formula, *HI* is the harvest index; *Y* is the seed yield of winter wheat (kg/hm²); and *B* is the amount of dry matter on the ground at the maturity stage of winter wheat (kg/hm²) [18].

Data Processing and Analysis Methods

The Figures and Tables involved in this paper were drawn using Excel 2021 and Origin 2021; significance test, correlation analysis, and regression analysis were completed using SPSS 26.0.

Results

Changes in Plant Height

Fig. 3 shows the dynamic variations in plant height and root length of winter wheat throughout the fertility period under different water and fertilizer regimes. It is evident that from the tillering to the maturity stage, the plant height of winter wheat in all treatments exhibited a consistent upward trend. Wheat growth was most vigorous, and plant height changes were most pronounced from the regreening stage to the jointing stage, after which it gradually slowed until stabilizing during the filling stage. At the tillering stage, the plant heights of all fertilized treatments surpassed those of

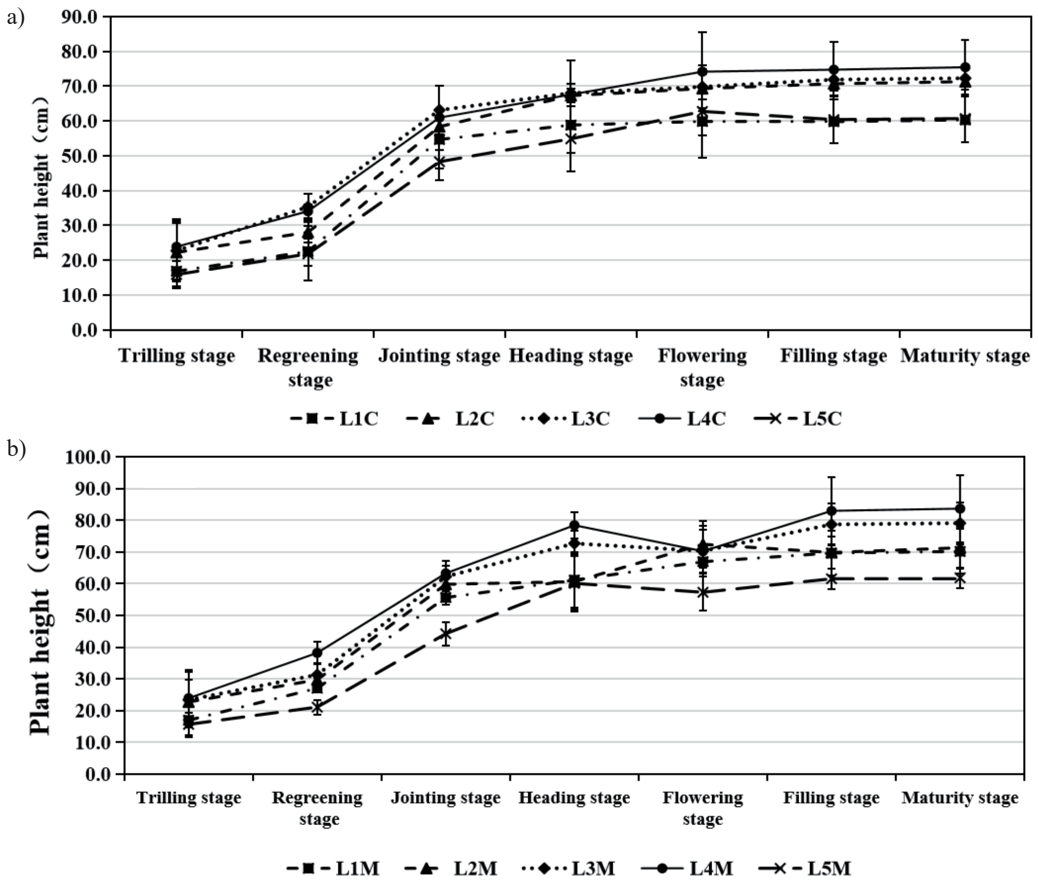

Fig. 3. Changes in plant height under different water and fertilizer patterns. a) is the sufficient irrigation; b) is the non-sufficient irrigation.

the no-fertilizer treatment. Specifically, the L2, L3, and L4 treatments did not significantly differ from each other, showing increases of 42.47%, 46.22%, and 51.4% compared to L5, respectively. The plant height of L1 did not significantly differ from L5 (Δ = 1.12 cm), indicating that early-stage fertilizer application accelerated winter wheat growth, with increasing fertilizer amounts leading to higher plant heights. Notably, insufficient irrigation enhanced plant height in fertilized treatments compared to sufficient irrigation, while the no-fertilizer treatment exhibited relatively higher plant height under sufficient irrigation. From the tillering to the jointing stage, winter wheat plant height increased by ≥20 cm. Sufficient irrigation resulted in slightly higher plant height in the L3 treatment compared to insufficient irrigation, with differences of 4.02 cm and 0.84 cm, respectively. From the heading to the filling stage, the growth rate of plant height slowed across different fertilizer treatments under both irrigation conditions. Notably, the growth rate of plant height in organic fertilizer treatments was significantly higher than in sufficiently irrigated treatments at the end of the winter wheat growth period under insufficient irrigation, while the opposite was observed for single-applied fertilizer and no-fertilizer treatments. At the maturity stage, plant heights varied across different fertilizer rates under sufficient irrigation, with L4 > L3 > L2 > L1 > L5, and the L4C treatment displaying the tallest plants at 75.44 cm. However, even without sufficient irrigation, the L4 treatment still exhibited a taller plant height of 79.7 cm, indicating that controlled irrigation at the end of the growth stage could promote winter wheat growth.

Changes in Root Length

Fig. 4 illustrates the dynamic changes in root length of winter wheat at different growth stages. As the fertility period progressed, the root length of winter wheat continued to increase, with the most notable increase observed from the regreening stage to the jointing stage. Subsequently, the rate of increase slowed down, reaching its maximum value during the filling period. Throughout the entire growth stage, the L4 treatment consistently exhibited the longest root length, measuring 15.6 cm, followed by the L1, L3, L2, and L5 treatments. By the end of the growth stage, the root lengths of L1, L2, L3, and L4 were, on average, 0.86 cm, 0.38 cm, 0.62 cm, and 2.16 cm higher, respectively, than those of the control group. Compared to the no-fertilizer treatment, each fertilizer treatment led to a significant increase in the root length of winter wheat. At the regreening stage, the fertilizer treatments experienced the greatest changes in root length, with increases ranging from 35.15% to 59.1% compared to the L5 treatment. From the jointing to the heading stage, the root length of the L1, L2, and L3 treatments exhibited

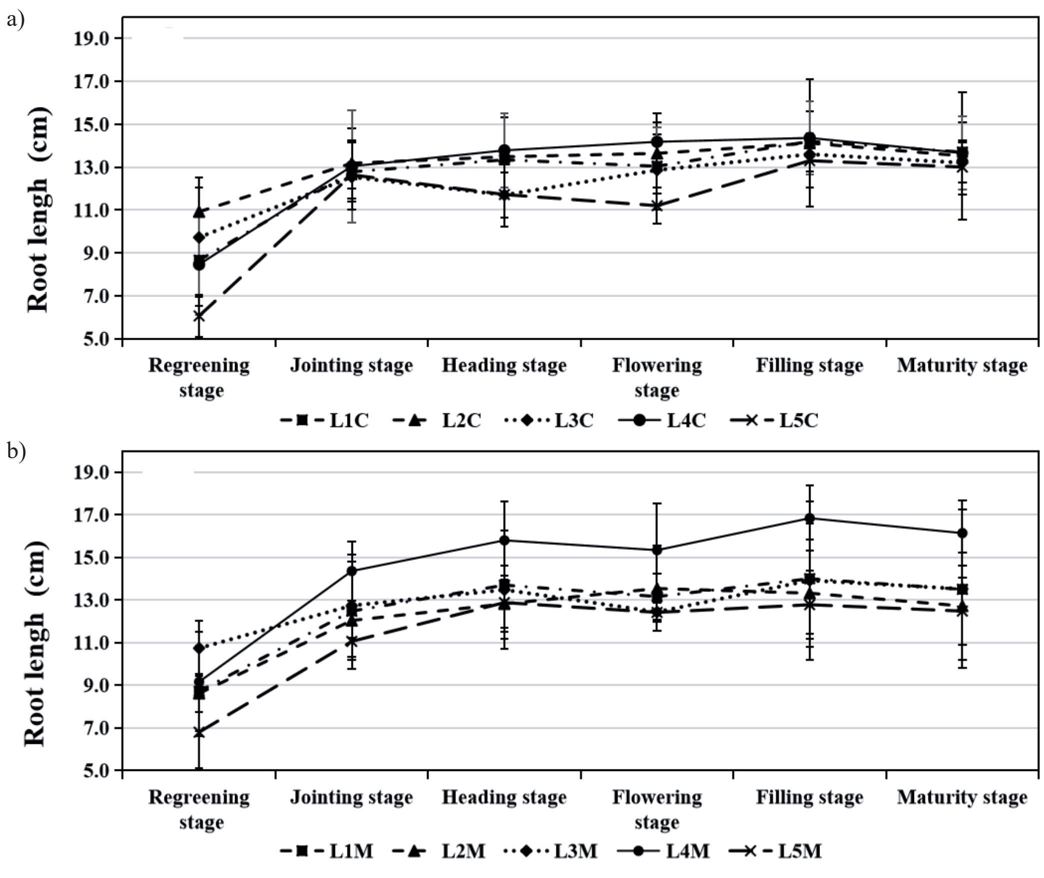

Fig. 4. Changes in root length under different water and fertilizer patterns. a) is the sufficient irrigation; b) is the non-sufficient irrigation.

relatively slower growth, with the growth rate of L1 > L2 > L3. However, the root growth of the single fertilizer treatment remained faster, with a growth rate of approximately 67.88%. At the flowering stage, changes in root length among treatments were less apparent, but compared to the no-fertilizer treatment, fertilizer treatments showed larger changes, increasing by 10.92% to 16.51%. The maximum root length of winter wheat was observed during the filling stage, ranging from 13.04 cm to 15.6 cm across treatments. The effect of irrigation volume on root length changes in winter wheat at each stage was not significant. However, for different fertilizer treatments, sufficient irrigation significantly increased the root length of winter wheat at each stage for the L2 treatment, albeit with a smaller average growth rate. In contrast, insufficient irrigation had a significant effect on treatments with higher fertilizer rates, particularly improving the root lengths of winter wheat in the L3 and L4 treatments by 0.53 cm and 1.36 cm, respectively. The effects of irrigation water volume were consistent for the L1 and L5 treatments.

Changes in Leaf Area Index

Fig. 5 depicts the leaf area index (LAI) of winter wheat at various growth stages, showing its relationship with different fertilizer rates and irrigation amounts. During the regreening stage, the effect of fertilizer rates on winter wheat LAI followed the order of L4 > L3 > L2 > L1 > L5, with fertilizer treatments surpassing the no-fertilizer treatment by 1.327, 1.171, 0.815, and 0.684, respectively. At the jointing stage, LAI did not fluctuate significantly, with treatments showing slight increases ranging from 1.19% to 9.16% compared to the regreening stage. At the heading stage, under sufficient irrigation, fertilizer treatments reached peak values, with L4 exhibiting the highest value. Conversely, under insufficient irrigation, peak LAI values were observed at the flowering stage, with L3M displaying the highest value. Toward the end of the growth stage, LAI values of winter wheat in each treatment decreased and stabilized at the filling and maturity stages, with L3 and L4 treatments showing similar LAI values of approximately 1.9. Comparing the effects of the two irrigation quantities, it is apparent that under insufficient irrigation, LAI increased throughout the growth stage for the L2, L3, L4, and L5 treatments, with L3 showing the largest average increase. However, the LAI increase for the L1 treatment was relatively lower, with insufficient irrigation promoting its growth by only 9%. At different growth stages, irrigation had varying effects on winter wheat LAI enhancement. In the early growth stage, insufficient irrigation had a more significant promoting effect on inorganic fertilizer alone, with L4 showing the highest average increase of 31.1%, substantially higher than the no-fertilizer treatment. However,

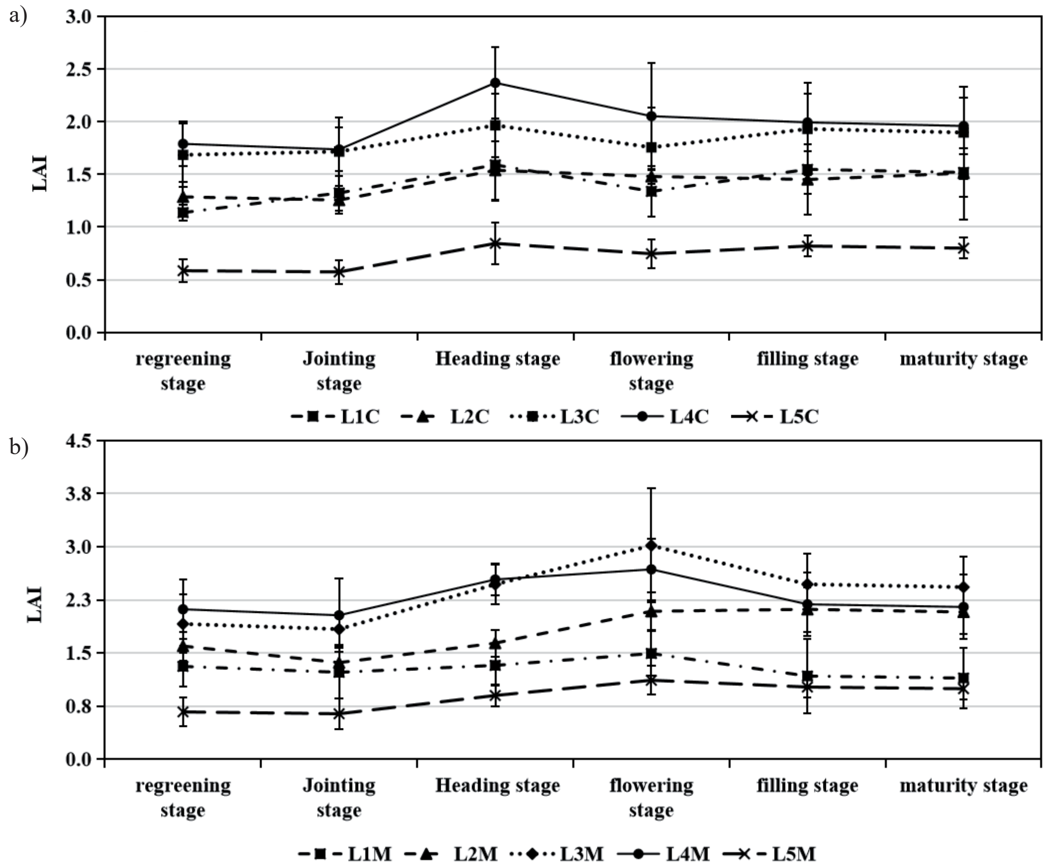

Fig. 5. Changes in leaf area index under different water and fertilizer patterns. a) is the sufficient irrigation; b) is the non-sufficient irrigation.

the effect of organic fertilizer alone was less pronounced, with only a 5.7% increase compared to the no-fertilizer treatment. In the late reproductive stage, the effect of insufficient irrigation on LAI enhancement of winter wheat containing organic fertilizer treatments was more substantial. From the heading stage onward, the LAI enhancement effects of the L3 and L2 treatments were significantly higher than those of the L4 treatment, with average increases of 13.6% and 11.9% higher, respectively. Consequently, the L3M treatment exhibited higher LAI than other treatments at the maturity stage.

Changes in SPAD Content

In Fig. 6, the relative chlorophyll content (SPAD) of winter wheat leaves under various water-fertilizer ratios exhibited an increasing trend followed by a decrease, reaching its peak at the heading stage and gradually declining thereafter. Different water and fertilizer treatments influenced the SPAD of the flag leaf and the second inverted leaf differently across fertility stages, although the overall differences were not significant. At the heading stage (Fig. 6a) and b)), the average SPAD of the flag leaf and the second inverted leaf of winter wheat in the L4 treatment was relatively high, approximately 41.28 and 39.89, respectively. Due to the slow decomposition of organic fertilizers, the SPAD of the organic fertilizer alone and the no-fertilizer treatment were similar. During the jointing stage, the average SPAD difference between the no-fertilizer and fertilizer treatments was most pronounced, with values ranging from 6.91 to 10.48 for the flag leaf and from 9.19 to 10.88 for the second inverted leaf. Notably, the L2 treatment exhibited the highest chlorophyll content at this stage. While the maximum SPAD was observed at the heading stage, the flag leaf and the second inverted leaf displayed different patterns of change under different fertilizer rates. For the flag leaf, the single fertilizer treatment showed the highest SPAD at 62.69, whereas the high fertilizer treatment in the second inverted leaf had a higher SPAD at 65.27, resulting in the highest relative chlorophyll content in the L3 treatment. Toward the later part of the growth stage, winter wheat chlorophyll content decreased slightly, but the reduction was minimal. During the flowering stage, the average SPAD range of the flag leaf in fertilized treatments was 56~58, while that of the second inverted leaf was 57~59. Chlorophyll content slightly increased during the filling stage, with insignificant differences among fertilized treatments. Throughout the growth stage, the chlorophyll content of winter wheat with fertilization treatments exceeded that of the control group. The effect of irrigation volume on winter wheat chlorophyll content was not significant but displayed some regularity in later fertility stages. During the flowering stage, insufficient irrigation increased chlorophyll content of winter wheat, with corresponding increases ranging from 0.2% to 8.14% across fertilizer treatments. Similarly, at the filling stage, L1, L2, L3, and L4 treatments exhibited similar chlorophyll content patterns as during the flowering stage, while the control group showed opposite changes, with higher SPAD in the L5 treatment under sufficient irrigation.

Changes in Tr, Pn, and Gs

Fig. 7 illustrates the transpiration rate (Tr), photosynthetic rate (Pn), and leaf stomatal conductance (Gs) of winter wheat under different water and fertilizer

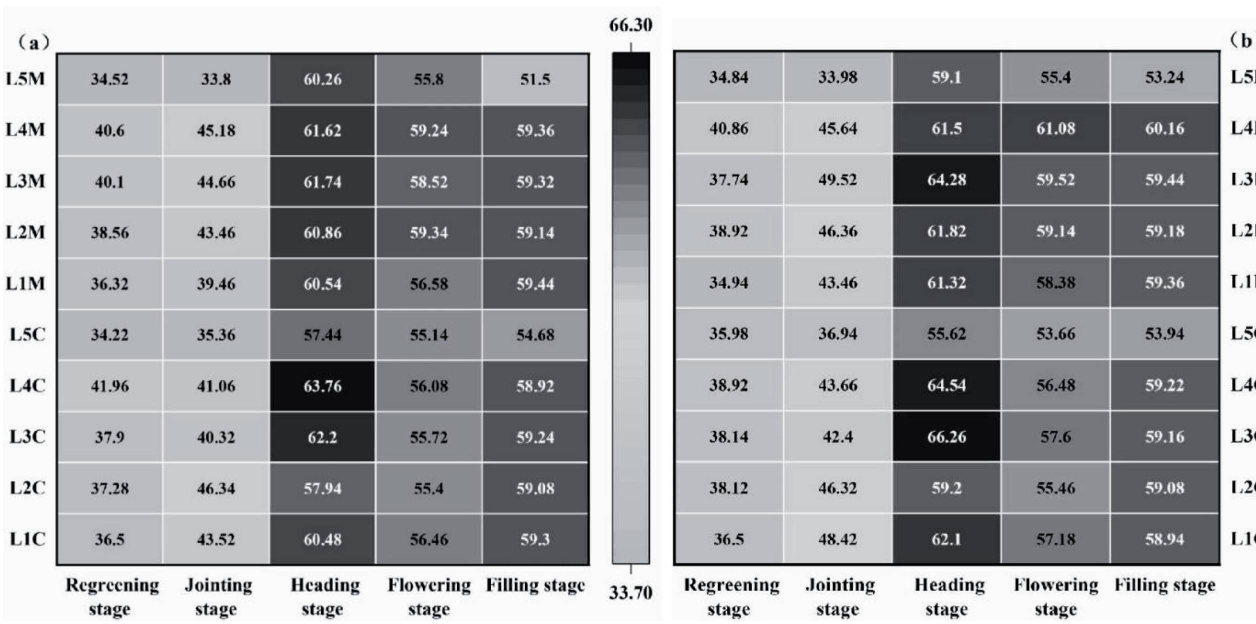

Fig. 6. Changes in SPAD content under different water and fertilizer patterns. a) is the sufficient irrigation; b) is the non-sufficient irrigation.

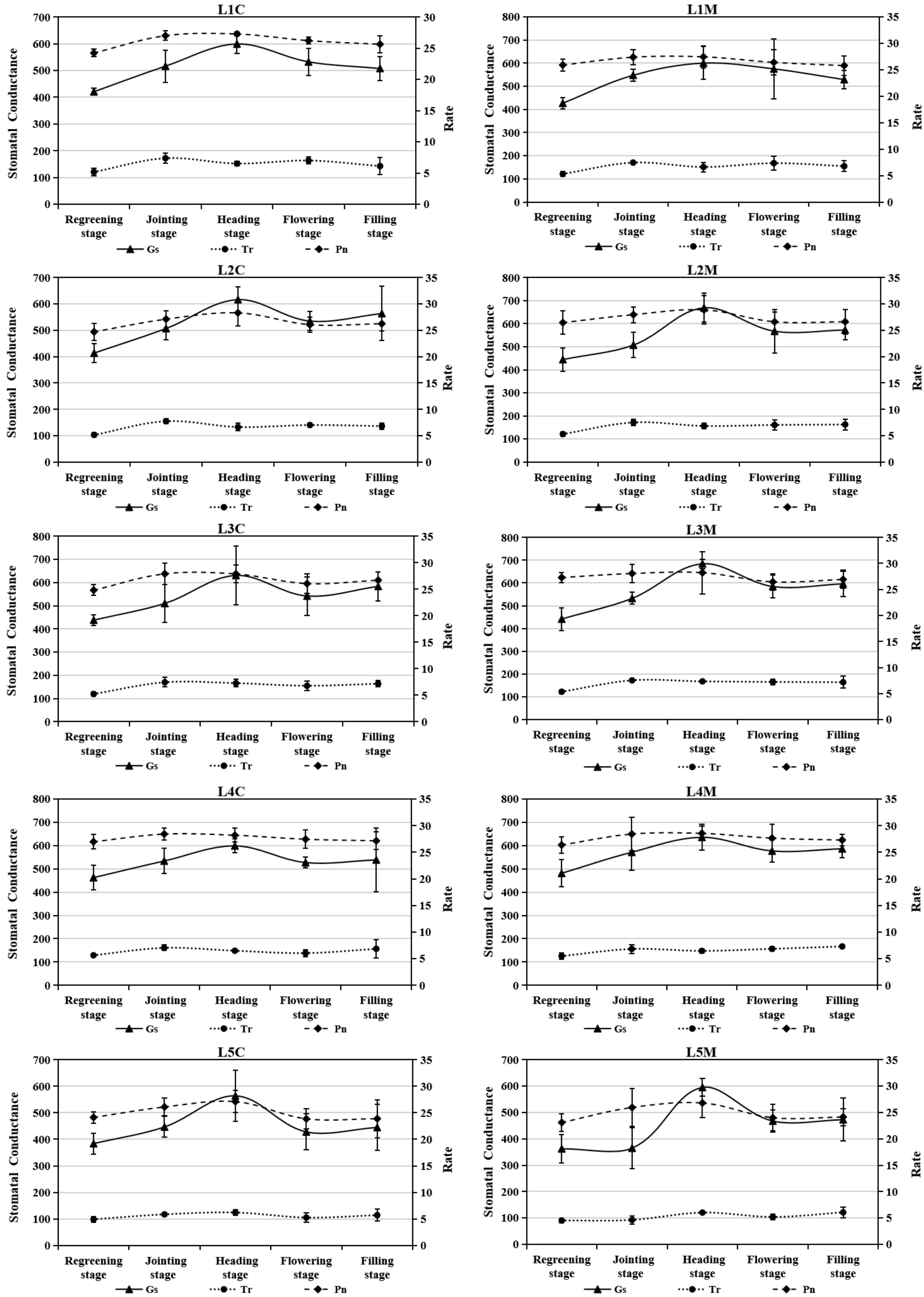

Fig. 7. Changes in photosynthetic indexes under different water and fertilizer patterns. Gs, Tr, and Pn denote leaf stomatal conductance (mmol/(m²·s)), transpiration rate (mmol/(m²·s)), and photosynthetic rate (μmol/(m²·s)), respectively.

treatments. Compared to the no-fertilizer treatment, various fertilizer ratios significantly enhanced the transpiration rate (Tr) of winter wheat. Tr exhibited a slight fluctuating trend throughout the growth stage. Among different fertilizer rates, Tr was highest under the L4 treatment, reaching 5.568 mmol/(m²·s) at the regreening stage, followed by L3 > L2 ≈ L1, which were 0.564, 0.501, and 0.509 mmol/(m²·s) higher than the control treatment, respectively. At the jointing stage, Tr displayed more significant changes, with increases ranging from 0.52 to 2.271 mmol/(m²·s). Notably, the winter wheat Tr of the L2 treatment was relatively high, with all four fertilization treatments averaging higher than the control by 1.685 to 2.252 mmol/(m²·s). After the jointing stage, Tr of treatments containing organic fertilizers was notably higher than those with chemical fertilizers alone. From the tassel stage to the flowering stage, the L1, L2, and L3 treatments were, on average, about 6.4%, 6.5%, and 11.5% higher than L4. During the filling stage, Tr with chemical fertilizer alone slightly increased, with L3 > L4 > L2 > L1 > L5 in terms of magnitude. Regarding different irrigation volumes, Tr significantly increased in treatments containing organic fertilizers throughout the growth stage, with the enhancement effect being more pronounced with higher organic fertilizer content. Specifically, the L1 treatment had the largest average increase of 0.261 mmol/(m²·s). For the L4 and L5 treatments, Tr was higher under sufficient irrigation than under insufficient irrigation during the pre-reproductive stage. However, by the flowering stage, the enhancement effect of insufficient irrigation on the L4 treatment became significant, with an average increase of 0.634 mmol/(m²·s), resulting in enhanced Tr of the L4 treatment at the end of the growth stage. Conversely, sufficient irrigation significantly increased the Tr of the no-fertilizer treatment, with an average increase of 0.297 mmol/(m²·s).

The photosynthetic rate (Pn) of winter wheat exhibited an increasing and then decreasing trend under different water and fertilizer patterns, as depicted in Fig. 7. Throughout the growth stage, Pn was slightly higher at the heading stage, while the other stages showed little variation. At the regreening stage, the highest Pn was observed in the L4 treatment, reaching 26.67 µmol/(m²·s), followed by L3 > L2 > L1, which were higher than the control by 2.432, 1.964, and 1.454 µmol/(m²·s), respectively. During the jointing stage, Pn under different water and fertilizer treatments showed more significant changes compared to the regreening stage, increasing by 1.749 to 2.408 µmol/(m²·s). The four fertilizer treatments were, on average, higher than the control by 1.167 to 2.391 µmol/(m²·s), with the single application of fertilizer treatment showing the highest Pn. At the heading stage, winter wheat Pn in the high organic fertilizer treatment was slightly higher than that in the chemical fertilizer alone application, with L2 reaching 28.599 µmol/(m²·s), followed by L4 > L3 > L1 > L5. Toward the end of the reproductive stage, Pn changes in winter wheat under all fertilizer treatments were smooth, with Pn in the chemical fertilizer–alone application returning to the maximum, averaging 27.641 µmol/(m²·s), followed by 26.329 to 27.027 µmol/(m²·s) in other treatments. Regarding the effect of irrigation volume on Pn, treatments containing organic fertilizer showed that insufficient irrigation significantly enhanced the Pn of winter wheat throughout the growth stage, with the highest enhancement effect observed for the high amount of organic fertilizer (L2 treatment), showing the largest average increase of 0.809 µmol/(m²·s). For the L4 treatment, Pn was greater under sufficient irrigation than under insufficient irrigation during the rejuvenation stage, but insufficient irrigation had a significant enhancement effect on the L4 treatment during the rest of the stage, with an average increase of 0.179 µmol/(m²·s). Conversely, sufficient irrigation was more effective in boosting the Pn of non-fertilized treatments, showing an average increase of 0.217 µmol/(m²·s).

Under the influence of temperature and light, the stomatal conductance (Gs) of winter wheat leaves under different water and fertilizer treatments exhibited an increasing and then decreasing trend, reaching its peak at the heading stage. Similar to the changes in Pn, at the regreening stage, the Gs of the L4 treatment was the highest, reaching 4471.734 mmol/(m²·s), followed by L3 > L2 ≈ L1. There was no significant difference between the single application of organic fertilizers and the high amount of organic fertilizers. The four fertilizer ratios were higher than that of the control group, ranging from 50.831 to 98.701 mmol/(m²·s). At the jointing stage, the four fertilization treatments showed an average increase in Gs ranging from 101.227 to 146.855 mmol/(m²·s) compared to the control, with the chemical fertilizer alone treatment exhibiting the highest Gs. The L1 showed the most significant enhancement effect compared to the regreening stage. During the heading stage, Gs for chemical fertilizer and organic fertilizer treatments were slightly higher, with L2 and L3 reaching 642.563 and 657.295 mmol/(m²·s), respectively, and the remaining treatments followed the order of L4 > L1> L5. Toward the end of the reproductive stage, Gs for each fertilization treatment decreased and then slightly increased, with treatments containing organic fertilizer showing slightly higher Gs compared to others. L1, L2, and L3 were approximately 1.762, -0.846, and 11.073 mmol/(m²·s) higher than L4, respectively. Insufficient irrigation could promote Gs to some extent, but the effect varied for treatments with and without fertilizer application. For treatments with fertilizer application, insufficient irrigation significantly enhanced Gs throughout the growth stage, with L1, L2, L3, and L4 showing average increases of 102.135, 124.935, 133.296, and 190.605 mmol/(m²·s), respectively, whereas insufficient irrigation had a weaker enhancement effect on the no-fertilizer treatment.

Changes in Yield Indicators of Winter Wheat

Changes in yield indexes of winter wheat under different water and fertilizer regimes are summarized in Table 3. Fertilizer application significantly influenced all relevant yield parameters of winter wheat, with the number of grains per spike, the number of effective spikes, and the yield of the L1, L2, L3, and L4 treatments being higher than that of the no-fertilizer treatment (L5). The thousand-grain weight and water content exhibited slight differences. Affected by aboveground indices, the harvest index (HI) of winter wheat in different water and fertilizer treatments exceeded 0.4, with significant differences observed among treatments. Under sufficient irrigation, the HI of the high fertilizer application treatment was higher than that of the other fertilized treatments, reaching 0.56. The relatively lower plant height and other growth indices of winter wheat in the no-fertilizer treatment led to lower yields and a relatively higher harvest index. The HI of different treatments under insufficient irrigation increased, with L3 ≈ L4 > L2 > L5 > L1. The HI of the high fertilizer application (L3) and single fertilizer application (L4) treatments was the highest at 0.57, while the HI of the L1 treatment was the lowest at 0.48. Compared to the two irrigation levels, insufficient irrigation elevated the HI for the fertilized treatments, with the HI of L1, L2, L3, and L4 increasing by about 19%, 1.44%, 1.72%, and 9.62%, respectively, compared to sufficient irrigation, with the most pronounced enhancement observed for organic fertilizer application alone.

The yield of winter wheat under various water and fertilizer treatments is illustrated in Fig. 8. Apart from the L5C treatment, the theoretical yield of winter wheat

Table 3. Effect of different water and fertilizer patterns on yield indexes of winter wheat.

	Number of grains per spike (grains)	Number of spikes per side (spikes)	Number of effective spikes (spikes)	1000 grain weight (g)	Moisture content (%)	Theoretical yield (kg/ha)	Actual yield (kg/ha)	Harvest index
L1C	34a	612bcd	580bc	42.33a	5.60d	10354.83abc	7976.23c	0.40c
L2C	25ab	561cbe	547cd	43.10a	6.74cd	8413.88c	8185.54bc	0.53abc
L3C	26ab	702abc	660abc	45.37a	7.08cd	9933.03abc	9363.38abc	0.56ab
L4C	31ab	697abc	650abc	41.13a	7.59bcd	10287.13abc	9057.62abc	0.52bc
L5C	19ab	409d	378e	42.23a	6.15d	3709.92d	4767.23d	0.56c
L1M	29ab	601bcd	566c	42.53a	8.29abc	9036.32bc	8357.53bc	0.48bc
L2M	28ab	747ab	724ab	44.00a	9.12ab	10943.62ab	10146.77ab	0.53abc
L3M	31ab	800a	760a	42.07a	10.22a	11670.80a	9811.28abc	0.57a
L4M	28ab	773ab	739a	42.20a	11.07a	10748.71abc	10485.51a	0.57bc
L5M	20b	459de	407de	41.13a	10.27a	4385.96d	4077.69d	0.52abc

Note: a, b, c, d, and e indicate differences in significance analysis.

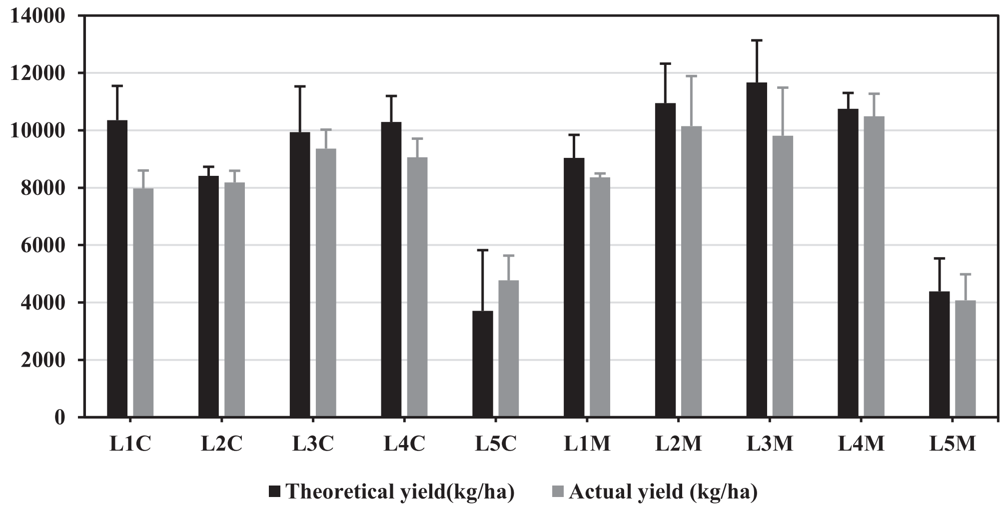

Fig. 8. Yield changes of winter wheat under different water and fertilizer patterns.

exceeded the actual yield, with the largest difference observed in the L1C treatment (Δ = 2378.6 kg/ha). The actual yield followed the order of L4 > L3 > L2 > L1 > L5, with the fertilizer treatments (L1, L2, L3, L4) yielding, on average, 84.67%, 107.26%, 116.79%, and 120.96% higher than the control group (L5). Hence, under the same nitrogen application conditions, the fertilizer treatment alone proved more effective in enhancing yield, followed by the high fertilizer ratio treatment. The highest yield of 9363.38 kg/ha was achieved in the high chemical fertilizer application L3C treatment under sufficient irrigation, which was 96.41% higher than the control and 3.38% higher than the single chemical fertilizer application treatment, followed by L4 > L2 > L1 > L5. Conversely, the highest yield of 10,485.51 kg/ha was recorded in L4, followed by 8357.53 kg/ha, 10,146.77 kg/ha, 9811.28 kg/ha, and 4077.69 kg/ha, respectively. Comparing the two irrigation levels, insufficient irrigation significantly boosted the yield of winter wheat, with the four fertilizer treatments respectively increasing the yield by 381.3 kg/ha, 1961.23 kg/ha, 447.9 kg/ha, and 1427.89 kg/ha, with the high organic fertilizer treatment showing the most significant effect. However, the yield of sufficiently irrigated winter wheat was slightly higher than that of insufficiently irrigated wheat under the no-fertilizer treatment. This indicates that when no fertilizer is applied, the crop absorbs enough water to compensate for the lack of fertilizer, resulting in an increased yield in the absence of fertilizer treatment under sufficient irrigation. Conversely, the addition of fertilizer slows down the effect of water and allows the crop to absorb the required nutrients, thus enhancing yield.

Correlation Analysis between Winter Wheat Yield and Crop Physiological Growth Indicators

Fig. 9 presents the correlation analysis between winter wheat yield and physiological growth indexes, revealing significant correlations between winter wheat yield and each physiological growth index. Except for the root length of winter wheat, yield demonstrated highly significant positive correlations ($p<0.05$) with plant height, LAI, SPAD, Tr, Pn, and Gs, with correlation coefficients of 0.8, 0.903, 0.934, 0.903, 0.958, and 0.918, respectively. Plant height exhibited highly significant positive correlations with LAI, Tr, Pn, and Gs (r = 0.834, 0.911, 0.872, and 0.861) and significant positive correlations with SPAD content (r = 0.66). LAI displayed highly significant positive correlations with Tr, Pn, and Gs, with correlation coefficients of 0.869, 0.916, and 0.895, respectively, and showed a significant correlation with SPAD content (r = 0.74). Among the physiological indexes, SPAD, Tr, Pn, and Gs showed positive correlations with each other, with SPAD and Tr displaying significant ($p<0.05$) correlations, and the remaining correlations being highly significant ($p<0.01$). It is evident that, apart from root length, the other physiological growth indexes significantly influenced the yield of winter wheat, with the indexes significantly affecting each other.

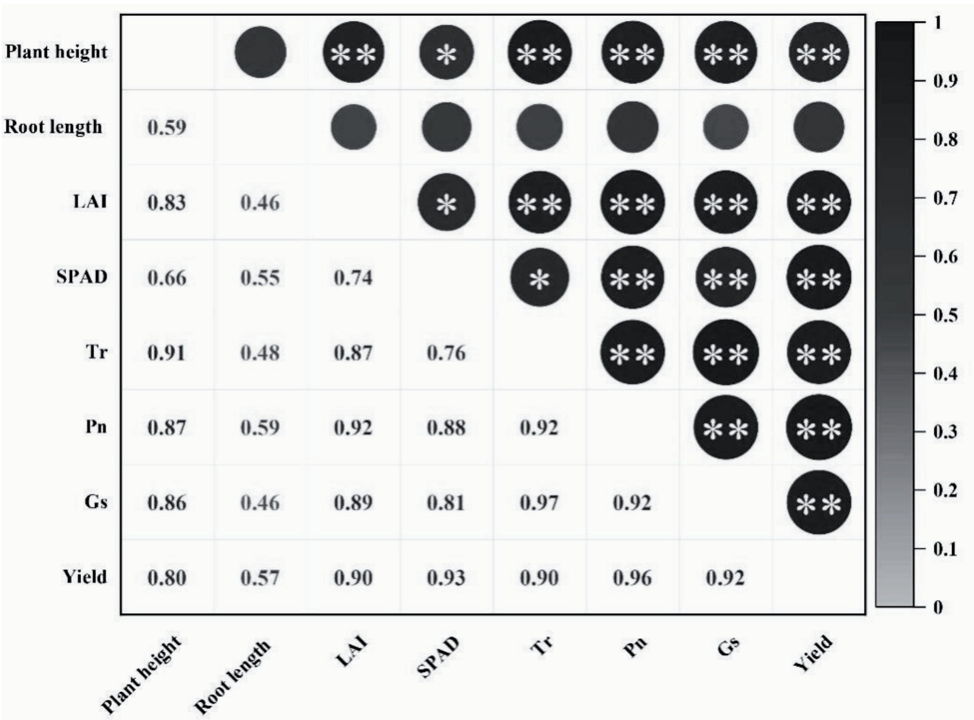

Fig. 9. Correlation analysis of yield and physiological growth indicators of winter wheat.
* indicates $p<0.05$, ** indicates $p<0.01$.

Regression Analysis between Yield and Crop Physiological Growth Indicators under Different Fertilizer Ratios

From Fig. 9, it is evident that the yield of winter wheat was highly significantly correlated ($p<0.01$) with plant height, LAI, SPAD, Tr, Pn, and Gs. The regression analysis between these six physiological growth indexes and yield under different fertilizer ratios is shown in Fig. 10, revealing that with the increase in plant height, LAI, SPAD, Tr, Pn, and Gs, yield increased accordingly. The yields of L1, L2, L3, and L4 were higher than that of the L5 treatment. For the plant height of winter wheat, the experimental results indicated that the plant heights of L1 and L5 at the end of the growth stage were lower, mainly concentrated below 70 cm. However, the single application of organic fertilizer significantly increased the yield of winter wheat. Under the same yield, the plant height of the L4 treatment was higher than that of the L3 and L2 treatments, and the difference between the plant heights of L3 and L2 was not significant. In Fig. 10b), the regression analysis of yield and leaf area index (LAI) showed significantly lower yields and LAI in the fertilizer-free treatments. Fig. 10c demonstrated that L2 and L3 had the highest foliar SPAD and yield, with the fertilizer-alone treatment slightly lower than the L3 treatment. There was little difference in yield with SPAD between L2 and L1 within a certain range.

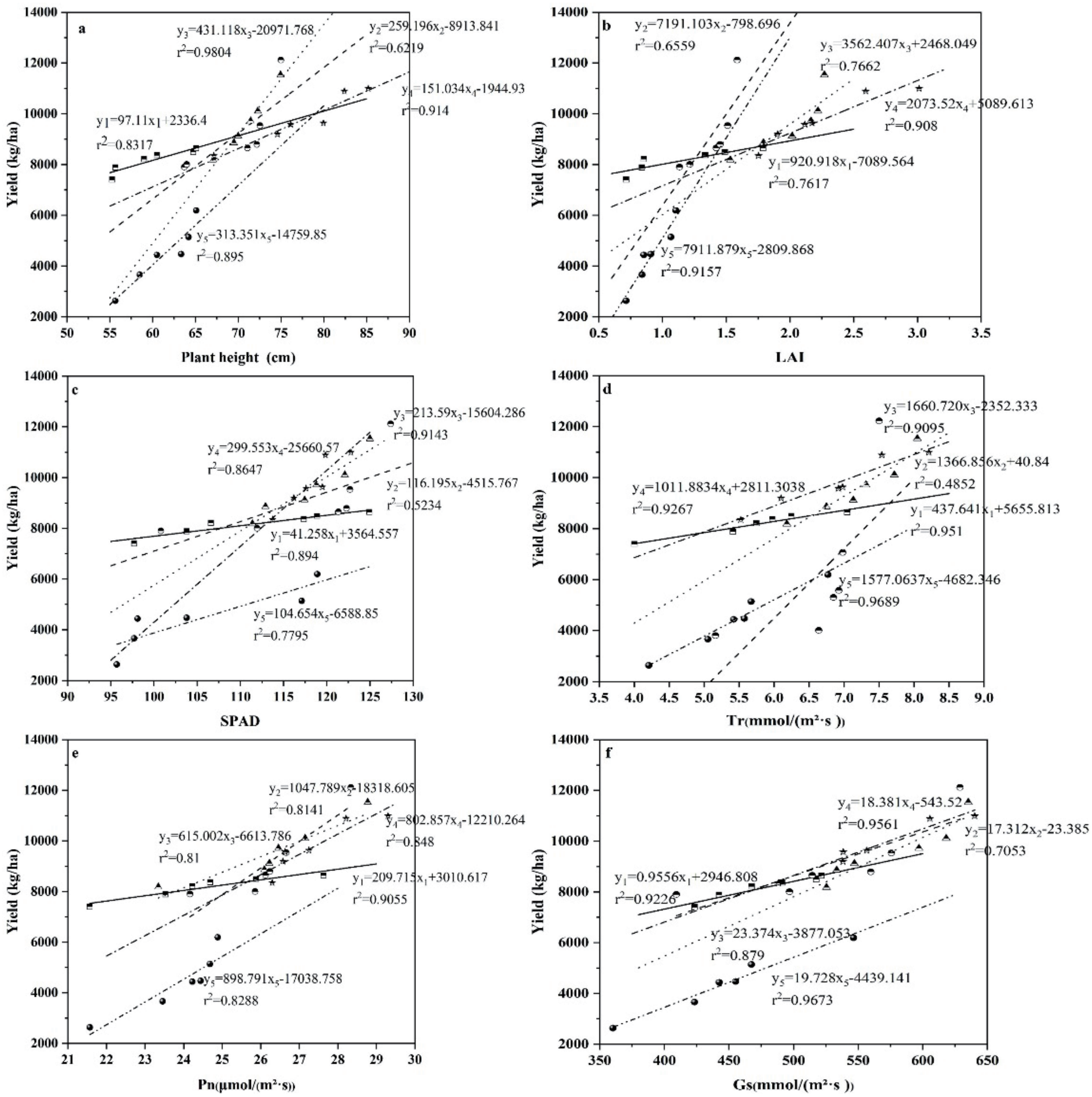

Fig. 10. Regression analysis of yield and various physiological growth indicators under different fertilizer ratios.
y1, y2, y3, y4, and y5 denote the regression analysis of L1, L2, L3, L4, and L5 with yield, respectively.

Regarding Fig. 10(d-f), the trends of yield with winter wheat Pn and Gs were similar, while Tr was slightly different. The yields of L2 and L5 were close to each other within a certain range for the Tr index, but the Tr of L2 was much larger than that of L5, which was the highest with the single application of chemical fertilizer. Changes in winter wheat yield with Pn and Gs for different fertilizer ratios did not differ much, except for L3, where the yield was higher with Pn than the rest of the treatments and lower with Gs. Under the same yield conditions, there was little difference among L2, L3, and L4.

Regression Analysis between Yield and Crop Physiological Growth Indicators under Different Irrigation Levels

The regression analysis of winter wheat yield and each physiological growth index under different irrigation levels showed (Fig. 11) that the relationship between yield and crop indexes conformed to a univariate primary regression. The variation of each indicator with yield under insufficient irrigation was significantly higher than that under sufficient irrigation, and the corresponding regression equations are shown in Fig. 11.

In summary, when comparing the effects of organic fertilizer alone with a combination of organic and chemical fertilizers on winter wheat growth, the latter proved to be more effective. However, in the short-term experiment, the immediate impact of high doses of chemical fertilizer or the application of chemical fertilizer alone surpassed that of organic fertilizer. Notably, insufficient irrigation significantly enhanced the physiological growth parameters of winter wheat under fertilizer treatments, consequently boosting yields. Therefore, considering the varied water and fertilizer regimes and their influence on winter wheat growth, as well as the correlation between physiological growth parameters and yield, it becomes apparent that in the short-term experiment, the combination of high chemical fertilizer doses or sole application of chemical fertilizer under conditions of insufficient irrigation yielded optimal results, with treatments L3 and L4 demonstrating relatively superior performance.

Discussion

Effects of Different Water and Fertilizer Patterns on Physiological Growth Indexes of Winter Wheat

Reasonable water and nitrogen availability play pivotal roles in optimizing wheat physiological growth, root characteristics, and enhancing yield [19, 20]. Plant height, being a prominent indicator of winter wheat growth, was significantly influenced by various water and fertilizer regimes. This study revealed that under consistent nitrogen application conditions, the plant

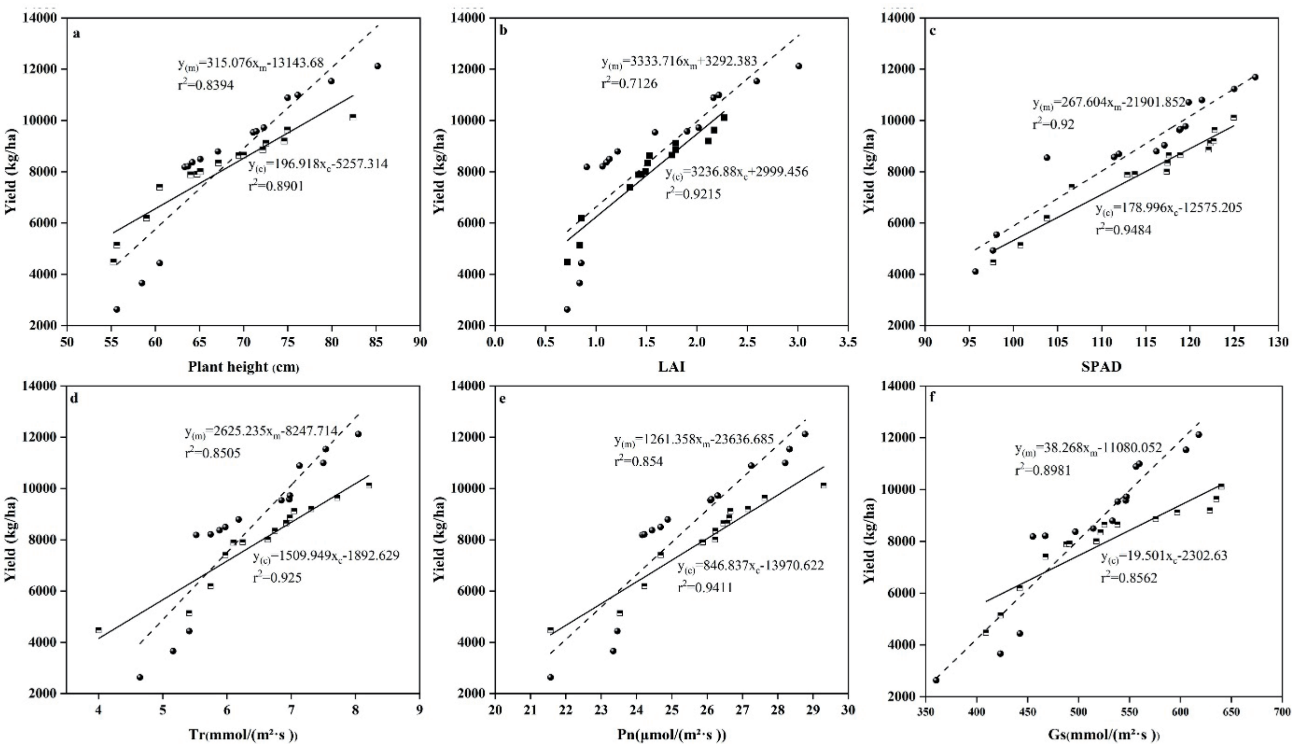

Fig. 11. Regression analysis of yield and various physiological growth indicators under different irrigation levels.
C and M denote sufficiently irrigated and non-sufficiently irrigated, respectively

height of treatment L3 was notably higher during the short-term experiment. Interestingly, reducing irrigation was not conducive to wheat plant height growth under the same nitrogen application conditions, while the impact of the organic fertilizer treatment was enhanced, aligning with findings from other researchers [21]. In this study, insufficient irrigation significantly enhanced the root length of winter wheat, and the effect was significant at the jointing stage, which was similar to the study on winter wheat growth indexes by Li et al. [22]. As the reproductive process advances, the root system's growth center shifts to deeper layers to enhance water and nutrient absorption, aiding in drought stress resistance [23, 24]. Hence, appropriate water management can stimulate root growth. When comparing different fertilizer treatment proportions, winter wheat root length showed a positive correlation with increasing fertilizer amounts. Although the trends in root length for treatments L1 and L5 were similar under the two irrigation amounts, the application of organic fertilizer in the later growth stages notably promoted root length. Leaf area expansion can partially mitigate the adverse effects of warming on wheat photosynthetic capacity [25]. Leaf area index (LAI), as a comprehensive index indicating light energy utilization and canopy structure, significantly influences crop photosynthesis. Different proportions of organic and inorganic fertilizers with varying ratios exerted significant effects on LAI. Treatment L4 exhibited higher LAI enhancement efficiency under sufficient irrigation, while treatment L3 steadily increased toward the end of the reproductive stage, eventually reaching a similar enhancement level as L4. Insufficient irrigation notably enhanced winter wheat LAI throughout the growth stage, prolonging LAI growth, delaying the emergence of the peak, and optimizing LAI at the end of the growth stage. Consequently, treatment L3 exhibited higher winter wheat yield at the maturity stage [26, 27].

Leaves are the organs of plants that primarily photosynthesize, producing carbohydrates that are ultimately used for plant development, growth, and reproduction. In this experiment, the SPAD contents of single winter wheat plants with different fertilizer rates were roughly shown as L4 ≈ L3 > L2 > L1 > L5, with greater differences in SPAD among fertilizer treatments in the early reproductive stage. This phenomenon can be attributed to the warming climate, which stimulates leaf area index (LAI) growth and increases SPAD and Pn [25], coupled with the slower decomposition of organic fertilizers, leading to higher SPAD in treatments L3 and L4. This results in larger disparities in SPAD among winter wheat plants with different fertilizer ratios in the pre-fertility stage. However, as the temperature rises after the flowering stage, leaf senescence accelerates, leading to a reduction in leaf chlorophyll content and photosynthesis rate, consequently decreasing SPAD and photosynthesis (Pn) in winter wheat at later stages. Contrary to this, a study by Li et al. [28] demonstrated that reduced application of organic fertilizer could enhance photosynthesis in wheat and delay leaf senescence. In the present experiment, photosynthesis increased in all fertilization treatments compared to the no-fertilizer treatment. However, transpiration (Tr) and stomatal conductance (Gs) were higher in winter wheat treated with high amounts of chemical fertilizer, which was contrary to the results of Hou et al. [29]. Additionally, the impact of irrigation amount on the photosynthesis of winter wheat at different fertility stages was not significant, but Tr, Pn, and leaf Gs of the no-fertilization treatments tended to decrease overall with decreasing irrigation amount, echoing findings by Gao et al. [30]. Notably, all four fertilization treatments with insufficient irrigation displayed enhanced photosynthetic capacity. Hence, for optimal winter wheat growth, it is imperative to integrate fertilizer applications (considering different types, rates, frequencies, etc.) with water management [31].

Effect of Different Water and Fertilizer Patterns on Yield of Winter Wheat

Chemical fertilizers, known for their quick-acting nature, can meet the nutrient demands of wheat during the pre-growth stage. On the other hand, organic fertilizers, with their comprehensive nutrient profile and longer efficacy, play a crucial role in the late growth stages, ultimately enhancing both yield and crop quality [32]. However, the present study revealed that the highest yield of winter wheat was attained in treatments L3 and L4 under insufficient irrigation. Interestingly, the effect of fertilizer was more pronounced in the short-term experiments, although fertilizer application inhibited water uptake by the crop. Despite this inhibition, fertilized treatments still yielded higher outputs under insufficient irrigation, contrasting with the no-fertilizer treatments. Similarly, Hassouniet et al. [33] found that under water stress, deep-rooted wheat exhibited increased thousand-grain weight and yield. Winter wheat could leverage its more developed root characteristics to absorb more water and nutrients under conditions of insufficient irrigation [23], thereby enhancing thousand-grain weight, the number of spikes, and yield [24, 34]. In this study, it was observed that the yield of winter wheat was closely related to various physiological parameters, including plant height, LAI, SPAD, Tr, Pn, and Gs, showing a highly significant positive correlation ($p<0.05$). This finding aligns with similar patterns reported by Yang et al. [35]. However, it is worth noting that while some indicators exhibited positive correlations, others showed no correlation or even negative correlations with average yield. Therefore, there exists a trade-off between yield components, implying that a decrease in certain yield components may not necessarily lead to a decrease in grain yield [36].

Conclusions

The study found significant effects of different water and fertilizer patterns on the physiological growth indexes and yield of winter wheat, with the fertilizer ratio exerting a more pronounced influence throughout the growth stages ($p<0.01$). In the short-term experiment, winter wheat growth was notably better with a high application of chemical fertilizers or a single application of organic fertilizers, resulting in relatively higher yields of 9363.38 kg/ha and 9057.62 kg/ha, respectively. Insufficient irrigation significantly increased various physiological parameters such as plant height, root length, LAI, SPAD, Tr, Pn, and Gs under fertilized conditions. However, non-fertilized treatments tended to exhibit better physiological indexes under sufficient irrigation. When comparing the two irrigation levels, insufficient irrigation notably boosted winter wheat yield across different fertilized treatments, with the highest enhancement observed in treatments with a high amount of organic fertilizer. Specifically, treatment L4 yielded the highest at 10,485.51 kg/ha. The study revealed a positive correlation between winter wheat yield and several physiological parameters, including plant height, LAI, SPAD, Tr, Pn, and Gs, indicating the importance of these factors in determining yield. Overall, the results suggest that a high amount of chemical fertilizer or a single application of chemical fertilizer under insufficient irrigation conditions was more effective in the short-term experiment, with treatments L3 and L4 showing relatively better performance.

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Conflict of Interest

The authors declare no conflict of interest.

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