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Evaluating Optimum Limited Irrigation and Integrated Nutrient Management Strategies for Wheat Growth, Yield and Quality

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Abstract: Agricultural productivity is significantly influenced by the restricted availability of irrigation water and poor soil health. To assess the influence of different potential soil moisture deficit (PSMD) regimes and integrated nutrient levels on the growth, yield, and quality of wheat, an experiment was carried out at the research area of the University of Agriculture, Faisalabad. The experiment includes three levels of PSMD (I_1: 25 mm PSMD, I_2: 50 mm PSMD, and I_3: 75 mm PSMD) and four integrated nutrition levels (N_1: 50% organic manure + 50% Inorganic NPK, N_2: 75% organic manure + 25% inorganic NPK, N_3: 100% application of organic manure, and N_4: 100% application of inorganic NPK). Results of the experiment revealed that maximum grain yield (4.78 t ha^{-1}) was obtained as a result of irrigation at 50 mm PSMD with the combined use of organic and inorganic sources in equal proportions. In contrast, the minimum yield was observed at I_3: 75 mm PSMD with 100% application of organic manure. The highest plant height (99.11 cm), fertile tillers (284.4), 1000-grain weight (44.48 g), biological yield (14.82 t ha^{-1}), radiation use efficiency for grain yield (RUE_{GY}) (5.71 g MJ^{-1}), and radiation use efficiency for total dry matter (RUE_{TDM}) (2.15 g MJ^{-1}) were observed under N_1: 50% organic manure with 50% inorganic NPK treatment. The highest value of these parameters was also observed in I_2 (50 mm PSMD). The results of this study can be extended to arid and semi-arid regions, where deficit irrigation is a key strategy to address water crises and to meet sustainable development goals.

Keywords: irrigation management; grain yield; potential soil moisture deficit; protein; radiation use efficiency; total dry matter

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1. Introduction

Wheat (*Triticum aestivum* L.) is a major global dietary source, providing more than 70% of daily calories to people living in remote areas. It is highly nutritious, with substantial amounts of carbohydrates, minerals, proteins, and vitamins [1]. Around 21% of the world's food needs are met through wheat and it is grown on more than 200 million hectares [2]. Water is a vital component for living beings and its availability is decreasing over time [3,4]. In plants, water has several functions, such as uptake from roots and assimilates translocation, maintaining cell turgidity and serving as a medium for biochemical reactions, physiological processes, and sequestration of salts and toxic elements inside or outside of the plant tissues [5–7]. One of the major difficulties faced in wheat production is the depletion of irrigation water resources at an alarming rate [8]. Photosynthates production is highly sensitive to water deficit, and ultimately affects grain development [9]. In this scenario, the emphasis should switch from increasing the cropped area to increasing production per unit of water [10]. In Pakistan, wheat crop is challenged due to drought stress and the seasonal closure of canals. This scarcity can be adjusted by rescheduling irrigation (decreasing the amount of water applied to crop) so that it does not disturb grain production significantly [11,12]. Under limited water conditions, deficit irrigation is a useful approach; it has several irrigation practices, such as potential soil moisture deficit (PSMD), that use low levels of irrigation water without adversely affecting crop production. The basic aim of this irrigation scheduling approach is to enhance crop water use efficiency by using less water [13,14].

Inequitable and consistent use of mineral fertilizers in modern farming has led to the reduction of nutrients in soil solution that has harmful impacts on soil fertility and productivity [15]. The sole use of inorganic or organic fertilizers has both positive and negative effects on plant growth, nutrient availability, and soil health. Organic fertilizers improve the physical and biological activities of the soil, but they are relatively low in nutrients, so larger amounts are needed for plant growth [16]. Moreover, their availability to plants is slow [17]. However, inorganic fertilizer is usually immediate used and contains all the necessary nutrients that are directly available to plants. But the continuous use of inorganic fertilizers themselves causes soil organic matter degradation, soil acidity, and environmental pollution [15]. Therefore, the integration of synthetic fertilizers and organic manures in proper proportions can be a beneficial and sustainable practice for better production and soil quality improvement [18]. Excessive dependence of inorganic fertilizers and ignorance of organic inputs under intensive cropping systems leads to degraded soil health and sub-optimal crop productivity [19]. Moreover, excessive use of chemical fertilizers results in contamination of groundwater [20,21]. Organic manure, along with chemical fertilizers, can make an impact on building soil fertility status and boosting crop productivity [22]. With integrated nutrient management, the organic matter of soil increases slowly; it may take several years but its contribution in boosting production is long-term and on a sustained basis [23]. Moreover, it aims to maintain the soil fertility and plant nutrient supply at an optimum level for sustaining the desired crop productivity through optimization of the benefits from all possible sources of plant nutrients in an integrated manner [24]. Therefore, the present study was planned to determine the best suitable combination of integrated nutrients and PSMD level to achieve higher growth and yield of wheat and to explore PSMD as an alternative approach for irrigation scheduling in wheat.

2. Materials and Methods

The proposed trial was conducted at the research area of the University of Agriculture, Faisalabad, Pakistan, during 2014–2015. The experimental area is located at 31°25′ North latitude, 73°04′ East longitudes, 184 m altitude, and has a semi-arid climate. The prescribed experimental area was preferred due to canal water availability. Before initiating the experiment, soil samples (0–30 cm) were collected from the experimental site. Different soil parameters were assessed for samples. Samples were sieved through a 2-mm sieve after gently mixing, drying, and grinding. The soil physiochemical traits and nutrient status were analyzed using the protocol of George et al. [25] and presented in Table 1, along with a chemical analysis of farmyard manure and inorganic fertilizers. The mean monthly temperature and rainfall are described in Figure 1.

Table 1. Soil physical and chemical analysis of the experimental site and chemical analysis of farmyard manure and chemical fertilizers.

Parameter	Sand (%)	Silt (%)	Clay (%)	pH	EC dS m^{-1}	OM (%)	N (%)	P_2O_5 (ppm)	K_2O (ppm)
Value	45	21	34	7.9	4.5	1.23	0.069	16.4	256
Status	-	-	-	Alkaline	Saline	Medium	Medium	High	High
				Farmyard Manure					
Parameter	**pH**	**EC (ds m^{-1})**	**N (%)**	**P_2O_5 (%)**	**K_2O (%)**	**Zn (ppm)**		**Mn (ppm)**	
	7.46	2.60	1.26	1.29	0.84	74		363	
				Chemical Fertilizers					
Fertilizer	**N (%)**			**P_2O_5 (%)**				**K_2O (%)**	
Urea	46			-				-	
Diammonium phosphate	18			46				-	
Murate of Potash	-			-				60	

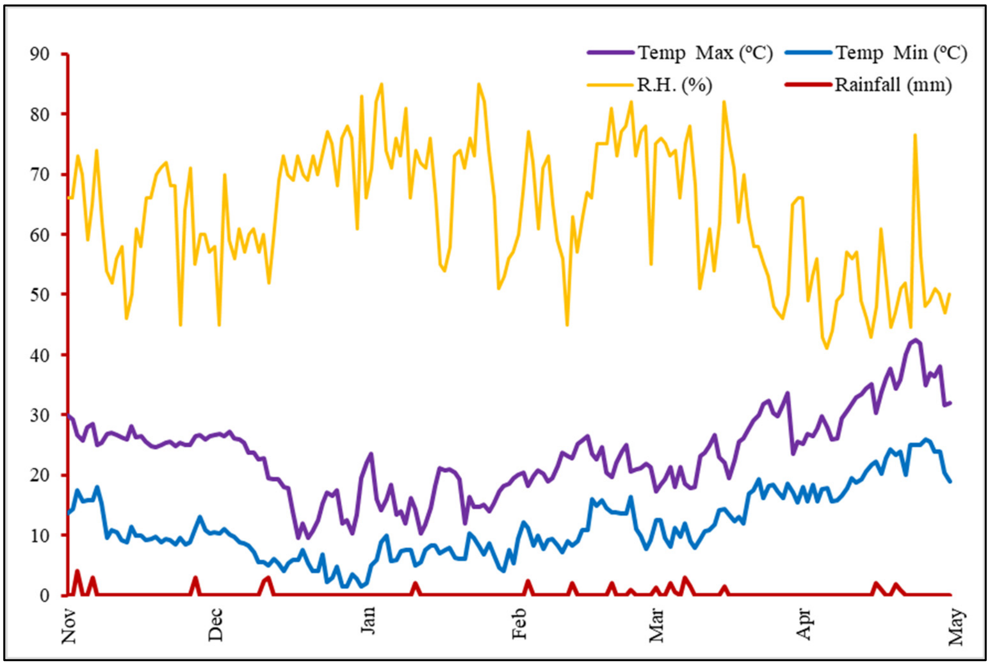

Figure 1. Summary of daily weather conditions at the experimental site.

2.1. Experimental Treatments and Design

The proposed study was laid out in a randomized complete block design with a split-plot arrangement and with three replications. The experiment has two factors: irrigation levels in main plots and integrated nutrients in sub-plots. Irrigation has three PSMD levels (I_1 = Irrigation at 25 mm PSMD, I_2 = Irrigation at 50 mm PSMD, and I_3 = Irrigation at 75 mm PSMD), while integrated nutrition is comprised of four levels (N_1 = 50% organic manure (FYM) + 50% inorganic (NPK); N_2 = 75% organic manure (FYM) + 25% inorganic (NPK); N_3 = 100% organic manure (FYM), and N_4 = 100% inorganic NPK).

2.2. Crop Husbandry

Seed of wheat cv. Galaxy-2013 was acquired from Wheat Research Institute, Faisalabad, and cultivated using the recommended seed rate at 100 kg ha^{-1} with a hand drill in rows that were 22.5 cm apart. The recommended doses of phosphorus (P) and potassium (K) were applied at sowing time. A half dose of nitrogen (N) was applied at the time of sowing and half was applied during the first irrigation. The sources of N, P, and K were urea, di-ammonium sulfate (DAP), and muriate of potash (MOP), respectively. All other cultural operations, such as intercultural practices, weeding, and plant protection measures, were kept constant in all treatments. For the application of irrigation, 25, 50, and 75 mm PSMD were referred to as standard. A standard model, "CROPWAT", was used to calculate penman's potential evapotranspiration. This model is developed by FAO [26]. It calculates that the total amount of water irrigated to crop is equal to the difference between the sum of rainfall and irrigation and potential evapotranspiration.

$$[D = \sum ETo - \sum (I + R)]$$

where D is deficit (mm), ET_o is evapotranspiration, R is rainfall, and I is irrigation.

ET_o was calculated by:

$$ETo = Epan \times Kp$$

where Epan is equal to the mean daily pan evaporation and Kp is equal to the pan coefficient.

A cut-throat flume was used to calculate the discharge of the watercourse (Table 2) as follows:

$$t = A \times d/Q$$

where t is time in seconds for a pre-determined amount of irrigation, A corresponds to the area of the plot to be irrigated (m^2), d is the depth of water to be applied (m), and Q is the discharge of the cut-throat flume (m^3 sec^{-1}).

Table 2. Irrigation applied to different treatments and rainfall received.

Date	I_1 mm	I_2 Mm	I_3 mm
26 November	60	60	75
9 December	25	-	-
19 December	-	-	-
2 January	25	50	-
16 January	-	-	75
30 January	25	-	-
11 February	25	50	-
26 February	25	-	75
6 March	-	-	-
14 March	25	50	-
Rainfall	29	29	29
Total	239	239	254

2.3. Procedure to Record the Observations

Observations regarding plant height, spike-bearing tillers, grains per spike, 1000-grain weight, grain yield, and biological yield were recorded according to standard procedures. Data regarding radiation use efficiency for total dry matter (RUE_{TDM} gMJ^{-1}) and grain yield (RUE_{GY} gMJ^{-1}) were recorded according to the formula [27]:

$$RUETDM = TDM/\sum Sa$$

$$RUEGY = Grain\ yield/\sum Sa$$

where 'TDM' is total dry matter and 'Sa' is the amount of intercepted photosynthetically active radiations as calculated by multiplying 'Fi' with 'Si', where 'Fi' is a fraction of intercepted radiations and 'Si' is the daily incident photosynthetically active radiation [28].

$$Sa = Fi \times Si$$

'Fi' was calculated by Beer's law:

$$Fi = 1 - \exp\left(-k \times LAI\right)$$

'K' is a coefficient whose value for wheat is 0.4 [29]. Furthermore, for the calculation of 'Si', there is a need to calculate solar radiations:

$$\text{Si} = \text{Total Rs}/2$$

Rs is equal to solar radiations that can be calculated by:

$$\text{Rs} = [\text{a} + \text{b}\ (\text{n}/\text{N})] \times\ \text{Ra}$$

where 'a' and 'b' are constants and have values of 0.25 and 0.5, respectively, n is equal to actual sunshine hours while N is the maximum possible sunshine hours, and Ra is extra-terrestrial radiations.

Measurement of leaf area was performed at 15-day intervals by randomly selecting ten plants from every subplot. The first sample was taken 25 days after sowing. In every sampling, fresh weight of separated leaves was measured, and 10 g of sub-sample was used to measure leaf area. Leaf area was calculated using the following method.

$$\text{Leaf area} = \text{Length}\ \times\ \text{Width}\ \times\ \text{K}$$

Leaf area index (LAI) was calculated by the following formula [30] :

$$\text{Leaf area index} = \text{Leaf area}/\text{Land area}$$

Leaf area duration (LAD) was measured as [31] :

$$\text{LAD} = (\text{LAI1} +\ \text{LAI2}) \times (\text{T2}-\text{T1})/2$$

Crop growth rate (CGR) was calculated by the method of Beadle, [32]

$$\text{CGR} = (\text{W2} - \text{W1})/(\text{T2} - \text{T1})$$

where W_1 and W_2 were the total dry weights harvested at times T_1 and T_2, respectively.

Total dry matter was determined after a regular interval of 15 days through a random selection of plants from each treatment and they were dried at 70 °C until constant weight was achieved, then they were weighed. Regarding quality characteristics, protein contents were determined using the Kjeldahl method [33]. Percent crude protein was determined using the following formula:

$$\text{Crude Protein}\ (\%) = (\text{V1} - \text{V2})\ \text{N}/100\text{W}\ \times 6.25 \times 14 \times 100$$

where 'V_1' is a sample of the titration, 'V_2' is the titration of volume, 'N' is the normality of standardized sulfuric acid, and 'W' is the weight of the sample. The starch content of wheat was estimated using an Omeg Analyzer G (Kernelyzer, Germany). Wheat grains were placed in a machine sample hopper using an 18-mm sample spacer and digital reading of starch was noted on the instrument display [34].

2.4. Statistical Analysis

The recorded data were statistically analyzed using Fisher's analysis of variance technique. Upon the signing of the treatments' effect, the least significance difference (LSD) was used to compare the treatment means [35].

3. Results

Water deficit levels and integrated nutrition significantly affected the LAI of wheat and LAI steadily increased from the start until a maximum point was reached, attained 90 days after sowing; it then declined gradually. PSMD levels significantly affected the LAI when irrigation was applied at I_2 (50 mm PSMD); this application most improved the LAI of wheat during the season, followed by treatment I_1 (25 mm PSMD); the lowest LAI response was observed in the case of I_3 (75 mm PSMD) (Figure 2A). In case of integrated nutrient levels, N_1 treatment substantially improved the LAI during the whole season, and it was highest 90 days after sowing, followed by N_4 as the next highest. On the other hand, the lowest LAI was recorded in treatment N_3. The sole application of organic manure (N_3) significantly reduced the LAI when compared to the combined use of organic and inorganic fertilizers (N_1) (Figure 2B). Among deficit levels, a higher deficit leads to a considerable decline in LAI; among integrated nutrient levels, sole use of organic manure leads to low LAI of wheat. A balanced combination of organic and inorganic manure results in the highest LAI. LAD is the duration for which actual sunlight is absorbed by the leaf area of a crop. LAD was significantly affected by water deficit and integrated nutrition levels and the highest LAD (during the whole season) was observed with I_2 treatment; treatment I_3 resulted in the lowest LAD (Figure 3A). Among integrated nutrient levels, the highest LAD was observed with N_1. In case of N_3, there was lesser vegetative growth; as a result, the lowest LAD was recorded (Figure 3B). CGR also showed a similar trend and irrigation regimes differed significantly. Irrigation treatment I_2 exhibited the highest CGR; the lowest CGR was recorded at a higher deficit level (I_3) (Figure 4A). Among integrated nutrient levels, N_1 resulted in higher CGR levels than other treatments (Figure 4B). The seasonal response of TDM was significantly influenced by irrigation regimes and different nutrition levels. The lowest TDM accumulation was noticed 25 days after sowing; after this point, it increased gradually, and it was highest after 90 days of sowing. Irrigation treatment I_2 attained the highest TDM accumulation, and these results were statistically at par with treatment I_1 (Figure 5A). Experimental plots treated with inorganic fertilizers in combination with FYM showed higher performance when compared to other treatments. The addition of 50% inorganic NPK and 50% FYM (N_1) achieved the highest TDM accumulation; this is in contrast to the N_3, that gave the lowest TDM accumulation (Figure 5B).

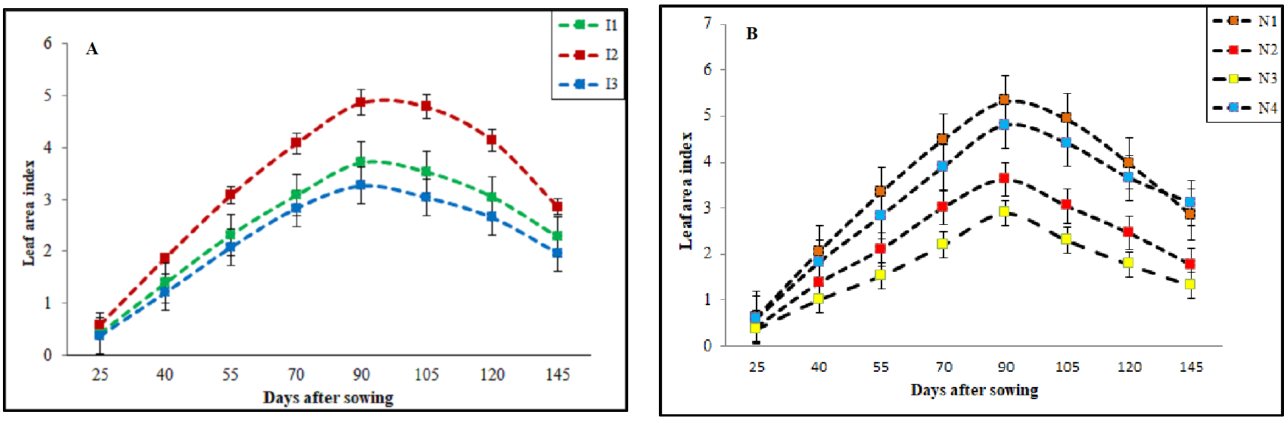

Figure 2. (**A**) Time course changes of leaf area index for irrigation regimes (**B**) for integrated nutrient levels.

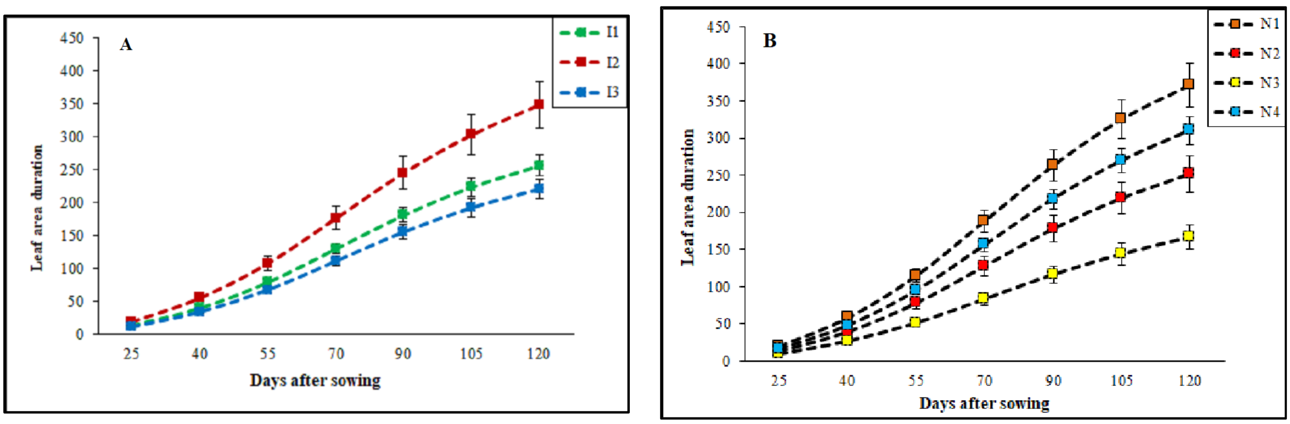

Figure 3. (**A**) Time course changes of leaf area duration for irrigation regimes (**B**) integrated nutrient evels.

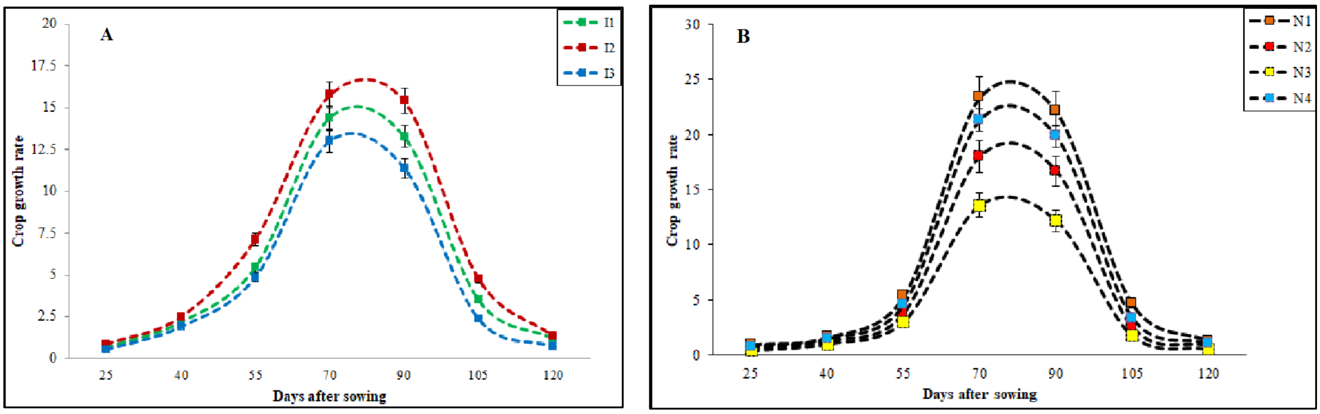

Figure 4. (**A**) Time course changes in crop growth rate for irrigation levels (**B**) integrated nutrient levels.

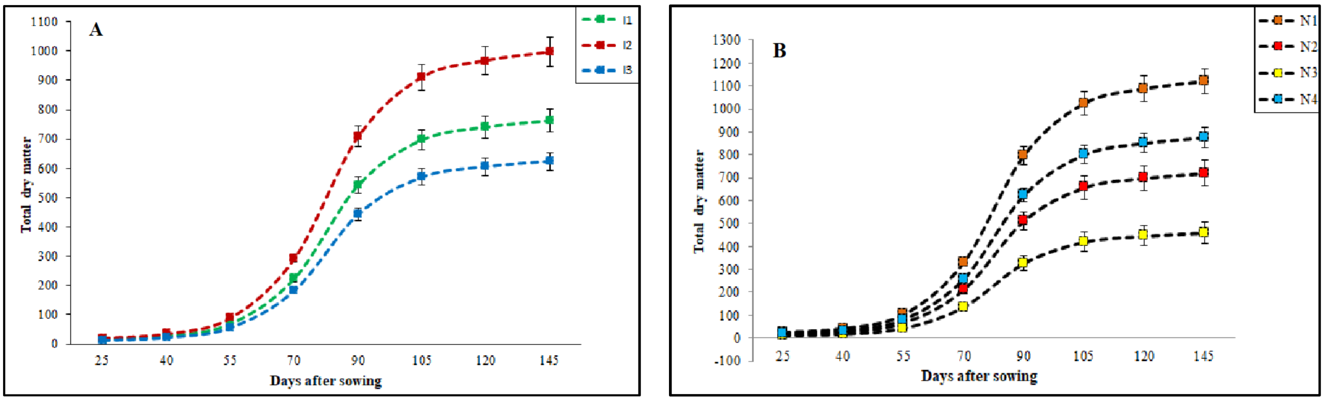

Figure 5. (**A**) Time course changes in dry matter for irrigation levels (**B**) integrated nutrient levels.

Plant height was significantly affected by both studied factors (irrigation levels and integrated nutrition) (Table 3) and the highest plant height (98.41 cm) was observed in I_2, followed by treatment I_1 (97.50 cm). Integrated nutrient levels differed significantly; it was highest with N_4 treatment (103.12 cm), followed by the N_1 treatment (99.11 cm). The lowest plant height was observed in treatment N_3. The interaction of both factors for plant height was found to be significant and the highest plant height was noticed in the combination of $I_2 \times N_4$. PSMD, integrated nutrient management, and the interaction of both factors showed a significant effect on yield and yield causative attributes. The significance of fertile tillers is evident from the fact that it directly influences grain production. The data regarding the spike-bearing tillers m^{-2}, as influenced by different deficit and integrated nutrient levels, are presented in Table 4. Among PSMD levels, the highest number of fertile tillers (282.25) was obtained in I_2 and the lowest number of productive tillers (222.83) was recorded in I_3. Regarding the response of integrated nutrients, the highest spike-bearing plants (284.44) were obtained in N_1, followed by N_4 (261.22). The minimum number of productive tillers (220.0) were obtained in N_3. The interactive effect of treatments for productive tillers was also significant and the highest number of productive tillers (319.0) were recorded in $I_2 \times N_1$. Grains per spike is an important yield contributing factor and its data are present in Table 4. Analysis of variance showed that water deficit and nutrition levels significantly differed and irrigation at I_2 produced the highest number of grains per spike (44.47), followed by I_1 (40.72) and I_3 (39.95). Individual comparison of treatment means for integrated nutrients revealed that the highest number of grains per spike (44.81) was recorded with N_1, followed by N_4 treatment (42.18). The lowest number of grains per spike (39.05) was noticed in treatment N_3. The interactive response $I_2 \times N_1$ produced the highest number of grains per spike (49.73) (Table 4).

Table 3. The mean squares of irrigation and integrated nutrient treatments about yield and yield components of wheat.

SOV	DF	Plant Height (cm)	Productive Tillers (m^{-2})	No. of Grains $Spike^{-1}$	1000-Grain Weight (g)	Biological Yield (t ha^{-1})	Grain Yield (t ha^{-1})	RUE_{TDM} (g MJ^{-1}	RUE_{GY} (g MJ^{-1})	Protein Contents (%)	Starch (%)
Replication (r)	2	5.25	136.7	0.68	0.80	0.05310	0.06680	0.007	0.003	0.02	0.51694
Irrigation (I)	2	64.66 **	10968 **	40.10 **	187.79 **	0.88148 **	0.80300 *	9.26 *	2.04	2.68 **	0.63361
Error a	4	1.934	261.8	1.96	0.36	0.01652	0.06712	0.03	0.001	0.03	0.14194
Nutrients (N)	3	289.8 **	6402.08 **	53.13 **	28.3 **	10.4427 **	3.32033 **	12.05 *	2.53 *	20.53 **	7.24630 **
I × N	6	5.38 *	1211.8 **	5.77 **	2.98 **	0.0314 *	0.11836 **	0.31	0.06	0.01	0.14769
Error b	18	1.67	256.1	0.44	0.73	0.0089	0.02436	0.001	0.001	0.01	0.13583
Total	35										

* = Significant at $p < 0.05$; ** = Significant at $p < 0.01$.

Table 4. The response of moisture deficit levels and integrated nutrient levels on yield and yield components of wheat.

Integrated Nutrient Levels (N)	I_1	I_2	I_3	Mean	I_1	I_2	I_3	Mean
	Plant Height (cm)				**Productive Tillers**			
N_1	97.9de	100.1cd	99.2cd	99.11b	301.3a	301.3a	233.0de	284.4a
N_2	90.9g	96.2ef	95.4f	94.21c	253.6cd	268.6bc	261.3c	261.2b
N_3	85.6h	92.7g	92.0 g	90.13b	231.0de	246.6cd	182.3f	220.0c
N_4	101.5bc	104.6a	103.2ab	103.1a	263.3c	294.6ab	214.6e	257.4b
Mean	97.50a	98.41a	94.01b		262.2b	282.2a	222.8c	
LSD ($p \leq 0.05$)	I = 1.57; N = 1.28; I × N = 2.22				I = 18.34; N = 15.85; I × N = 27.45			
	Grains Per Spike				**1000-Grain Weight (g)**			
N_1	42.16cde	49.76a	42.60cd	44.81a	43.79c	49.56a	40.09ef	44.48a
N_2	37.26g	42.93bc	40.36ef	40.18c	36.74g	42.45cd	35.10h	38.10c
N_3	39.13fg	40.70def	39.26f	39.70c	34.45h	39.41f	34.06h	35.97d
N_4	41.23cde	44.53b	40.73def	42.16b	41.20de	46.30b	37.62g	41.71b
Mean	40.74b	44.48a	39.95b		39.04b	44.43a	36.72c	
LSD ($p \leq 0.05$)	I = 1.02; N = 1.07; I × N = 1.87				I = 0.68; N = 0.84; I × N = 1.46			
	Biological Yield (t ha^{-1})				**Grain Yield (t ha^{-1})**			
N_1	14.78b	15.24a	14.44c	14.82a	4.53ab	4.78a	4.32bc	4.54a
N_2	13.37fg	13.53f	13.23g	13.37c	3.66d	4.37bc	3.30de	3.77c
N_3	12.27i	12.57h	12.06j	12.30d	3.10ef	3.23ef	3.02f	3.11d
N_4	14.11d	14.39c	13.84e	14.11b	4.05c	4.33bc	4.04c	4.14b
Mean	13.63b	13.93a	13.39c		3.83b	4.18a	3.67b	
LSD ($p \leq 0.05$)	I = 0.14; N = 0.09; I × N = 0.16				I = 0.29; N = 0.15; I × N = 0.26			

Means sharing same letters did not differ significantly at $p = 0.05$; I_1 = 25 mm PSMD; I_2 = 50 mm PSMD; I_3 = 75 mm PSMD; N_1 = 50% FYM + 50% inorganic (NPK); N_2 = 75% FYM + 25% inorganic (NPK); N_3 = 100% FYM; N_4 = 100% inorganic (NPK).

In PSMD levels, the highest 1000-grain weight (44.43 g) was obtained with treatment I_2; the lowest weight (36.72 g) was observed with treatment I_3 (Table 4). Various levels of integrated nutrients responded significantly; the highest 1000-grain weight (44.48 g) was found with N_1, followed by N_4 and N_2. The lowest 1000-grain weight (35.97 g) was recorded in treatment N_3. The total biomass produced by a crop from a unit area is termed as biological yield. This was significantly affected by deficit levels, integrated nutrients, and their interaction. The highest biomass (13.93 t ha^{-1}) was attained with treatment I_2 and minimum biological yield (13.39 t ha^{-1}) was observed in treatment I3. Individual comparison of treatment means regarding integrated nutrients presented in Table 4 revealed that the highest biological yield (14.82 t ha^{-1}) was found in treatment N_1, followed by N_4 and N_2. The lowest total biomass was observed in treatment N_3 (Table 4).

Analysis of variance for grain yield indicates that a significant response was achieved from irrigation and integrated nutrient treatments (Table 3). Regarding irrigation regimes, maximum yield (4.18 t ha^{-1}) was obtained in I_2, followed by treatments I_1 (3.83 t ha^{-1}) and I_3 (3.67 t ha^{-1}) (Table 4). Individual comparison of treatment means for different integrated nutrients revealed that the maximum value for grain yield (4.54 t ha^{-1}) was attained by treatment N_1, followed N_4 (4.14 t ha^{-1}) and N_2 (3.77 t ha^{-1}). Minimum grain yield (3.11 t ha^{-1}) was recorded in treatment N_3 (Table 4). Interaction between PSMD levels and integrated nutrient levels was also found to be significant and maximum grain yield (4.78 t ha^{-1}) was recorded in $I_2 \times N_1$. Meanwhile, minimum grain yield (3.02 t ha^{-1}) was obtained from combination $I_3 \times N_3$ (Table 4).

RUE_{TDM} and RUE_{GY} showed a significant effect on water deficit and integrated nutrient levels. The highest value of RUE_{TDM} was attained in I_2 (5.39 MJ^{-1} of intercepted radiation). The lowest RUE_{TDM} was observed where drought stress was high. With the comparison of treatment means of integrated nutrients, RUE_{TDM} varied from 3.84 to 5.36 MJ^{-1}. Treatment N_1 showed the highest RUE_{TDM} (5.36 MJ^{-1} of intercepted radiation); the lowest RUE (3.84 MJ^{-1} of intercepted radiation) was achieved in N_3. RUE_{GY} also differed significantly, and, in the case of integrated nutrients, it varied from 2.09 to 1.26 Mj^{-1} of intercepted radiation. It was highest in N_1. For PSMD levels, the highest RUE_{GY} was recorded in I_2 and the minimum was recorded in I_3 (Table 5).

Table 5. The response of moisture deficit levels and integrated nutrients on radiation use efficiency, protein, and starch contents.

Integrated Nutrient Levels (N)	I_1	I_2	I_3	Mean	I_1	I_2	I_3	Mean
	RUE_{TDM} (gMJ^{-1})				RUE_{GY} (gMJ^{-1})			
N_1	5.70d	6.55a	4.89e	5.71a	2.09c	2.70a	1.66e	2.15a
N_2	3.83h	5.76c	3.50j	4.36c	1.26h	1.88d	1.07j	1.40c
N_3	2.83k	3.62i	2.63l	3.03d	0.83k	1.13i	0.79l	1.79d
N_4	4.52f	6.16b	4.34g	5.01b	1.57f	2.37b	1.42g	2.15b
Mean	4.22b	5.52a	3.84c		1.43b	2.01a	1.22c	
LSD ($p \leq 0.05$)	I = 0.05; N = 0.03; I × N = 0.05				I = 0.03; N = 0.03; I × N = 0.05			
	Protein Contents (%)				Starch (%)			
N_1	10.10	10.46	9.60	10.06c	57.80	57.80	57.66	57.75b
N_2	11.06	11.63	10.70	11.13b	57.96	58.06	57.80	57.94b
N_3	12.10	12.73	11.80	12.21a	59.10	59.93	59.10	59.37a
N_4	8.60	9.23	8.20	8.67d	57.43	57.53	56.93	57.30c
Mean	10.47b	11.02a	10.07c		58.07	58.33a	57.87	
LSD ($p \leq 0.05$)	I = 0.22; N = 0.03				N = 0.36			

Means sharing same letters did not differ significantly at p = 0.05; I_1 = 25 mm PSMD; I_2 = 50 mm PSMD; I_3 = 75 mm PSMD; N_1 = 50% FYM + 50% inorganic (NPK); N_2 = 75% FYM + 25% inorganic (NPK); N_3 = 100% FYM; N_4 = 100% inorganic (NPK).

Protein contents showed a significant effect on water deficit and integrated nutrient levels. Among irrigation levels, treatment I_2 produced the highest protein contents (11.02%), followed by treatment I_1 and I_3, which produced 10.47% and 10.07%, respectively. Treatments regarding integrated nutrients also differed significantly for protein contents. Conversely from other parameters, in the case of protein contents, treatment N_3 attained the highest protein contents (12.21%), followed by treatment N_2 (11.13%). The lowest protein contents (8.67%) were observed in N_4 (Table 5). Starch contents in wheat were significantly affected by integrated nutrient levels. In protein contents, treatment N_3 showed the highest starch contents (59.37%) (Table 5).

4. Discussion

Appropriate frequency and intensity of irrigation water is a critical factor for optimum crop growth and productivity [36]. In this study, drought stress significantly reduced dry matter accumulation, radiation use efficiency, and growth-related characters (leaf area index, leaf area duration, net assimilation, and crop growth rate). However, integrated use of FYM and NPK boosted the growth and yield in wheat. According to Gustav et al. [37], Farooq et al. [38], and Taiz and Zeiger [39], growth and development of plants primarily depends upon three phases: Cell division, elongation, and differentiation. These stages are linked with several physiological, biochemical, and morphological processes. Each of the described processes are adversely affected by drought stress. Drought stress reduces turgor pressure by disrupting water flow from the xylem toward surrounding cells, resulting in stunted leaves and lower LAI. Under drought conditions, a significant reduction in leaf area index occurs due to reduced leaf area [40,41]. The present study reported that the combined application of FYM and NPK in equal proportions expressed a significant tendency to improve the growth traits in wheat crops. Integrated use of organic and inorganic nutrient sources produced the highest LAI, LAD, and CGR. The combination of inorganic nutrients with FYM improves leaf growth, photosynthetic efficacy, chlorophyll contents, and assimilation capacity, eventually increasing the leaf surface area [42].

The present study indicates that drought stress significantly reduced the fraction of intercepted radiation and cumulative photosynthetically active radiations. The decrease in intercepted radiations under reduced irrigation regimes might be the consequence of the decline in the surface area of leaves. Hayatu et al. [43] reported that a reduction in leaf area index, cumulative PAR, and Fi are due to impaired canopy development, change in leaf orientation, and accelerated senescence of leaves. Moreover, the incorporation of NPK with FYM (50% FYM + 50% NPK) significantly affected the cumulative PAR in drought stress conditions. A higher cumulative PAR, achieved by improving the leaf expansion through the addition of FYM with inorganic NPK, leads to the greater availability of essential nutrients. Application and incorporation of FYM decreases the evaporation losses, possibly due to root zone softness caused by manure, leading to higher root proliferation in the soil to fulfill water requirements [44]. It is confirmed in several studies that integrated nutrient management boosted crop growth due to greater and readily available access to nutrients [45,46]. Furthermore, it improves the water-holding capacity and biological properties of soil [47,48]. The combination of FYM with NPK not only meets macronutrient requirement but also provides micronutrients to soil [49]. TDM was also significantly affected by moisture stress. A decrease in total biomass due to drought stress was evident in this experiment. The decrease in TDM production is linked with stomatal closure and leads to a decrease in CO_2 fixation, consequently reducing cell division and elongation and limiting cellular metabolism [50]. TDM production was highest with the integrated application of inorganic NPK and FYM. Uikey et al. [51] described that the addition of FYM along with inorganic nutrients improves TDM production because the mechanism of release of nutrients from organic manures is slower; it helps microorganisms to decompose the manure and enhance nutrient availability that leads to the synthesis of protein and results in higher production of TDM.

In the current study, a significant decline in plant height was observed under drought (75 mm PSMD) as reported by Shehzad et al. [52]. According to Imam and Segha-Al-Islami [53] and Baroutzadeh et al. [54], deficit irrigation induces a reduction in plant height by reducing the plant respiration (less CO_2 absorption and reduced turgor pressure). An increase in plant height was observed alongside an increase in soil moisture; this is attributed to an increase in the number of internodes per stem [8]. Maximum plant height was achieved with the recommended application of inorganic fertilizer, as mineral fertilizers readily enhance vegetative growth because of their quick availability to crop plants [55]. Tillering was also significantly influenced by drought stress. Tillering was inversely proportional to drought stress as tillering decreases when drought stresses increases and vice versa. Shehzad et al. [52] documented that, at a higher level of water stress, the number of spike-bearing tillers reduced. Khan et al. [56] reported that by increasing irrigation frequency, the number of fertile tillers increased. Integrated use of FYM and NPK improved the number of productive tillers. The combined application of organic and mineral fertilizers helps to improve the tillering capacity of wheat [57,58]. Results regarding grains per spike were also noticeably influenced by PSMD levels; with an increase in the level of deficit, the number of grains per spike reduced. Grains per spike was positively affected by the integrated use of FYM and inorganic NPK. Considering the results of 1000-grain weight, grain yield, and biological yield, these parameters were significantly affected by drought stress. At a mild level of deficit, these parameters performed better. Bashir et al. [13] justify these results by reporting that agronomic traits, such as fertile tillers, grains per spike, test weight, and biological and grain yield, gave better results at 45 mm PSMD treatment. All yield contributing traits gave the best results when they were fertilized with an equal combination of FYM and inorganic NPK, as additions of both organic and mineral sources provide micronutrients and secondary nutrients along with macronutrients [59]. Integrated nutrient management improves fertilizer use efficiency and ensures higher yield on a sustained basis [60].

A gradual reduction in RUE_{TDM} was observed with drought due to a decline in leaf canopy, an increase in leaf senescence, and a reduction in photosynthetic efficiency [61]. A combined application of FYM and inorganic NPK caused a positive response in RUE_{TDM} due to higher dry matter production through rapid leaf area development by maximum interception of PAR. The rapid development of leaf area leads to rapid coverage of the ground surface, higher carbon capturing, and improved plant growth [62]. In a recent study, it was reported that, under an integrated nutrient system, there is higher availability of plant nutrients because of faster mineralization of organic matter in soil, leading to higher RUE_{TDM} [63]. Significant differences in RUE_{GY} were observed by irrigation regimes and integrated nutrients. We observed a substantial reduction in the RUE_{GY} of drought-affected plants due to a decrease in the duration of developmental phases. Water shortage reduces the grain yield which, in turn, drops the RUE_{GY}. Drought stress causes injury in various metabolic processes, such as a decrease in chlorophyll pigments leading to a reduction in RUEGY [64]. Proper application of water and fertilizer improves biomass accumulation, which is strongly linked with grain yield [65]. Integrated application of organic and mineral nutrients positively influenced the RUE_{GY} because the combination of nutrients improved the mobilization of nutrients; the involvement of nutrients in vegetative and grain-filling organs ultimately increased the RUE_{GY} [66].

Protein content in wheat grains was reduced with the increase in water stress and different levels of integrated nutrients. The highest protein percentage was recorded with the sole application of FYM manure. This is because organic manure leads to the accumulation of elevated amounts of seed components, such as $CaCO_3$ and increased lipid metabolism, which functions to enhance protein content in seed [67]. Similarly, the application of organic manures improved wheat starch content and protein content [68,69]. The results of this study can be used to meet sustainable development goals in the era of climate change and water crisis [70–72].

5. Conclusions

The physiological availability of water to plants is a key factor in crop production worldwide. The data suggest that there is still great scope to increase wheat productivity by sensible use of deficit irrigation. It is concluded from the study that deficit irrigation significantly influences crop growth and productivity. However, the combined use of organic and inorganic fertilizers showed a considerable response in the growth and yield of wheat under water deficit conditions. The result of the experiment indicated that integration of 50% FYM and 50% NPK produced the highest grain yield at 50 mm PSMD. Moreover, higher growth and radiation use efficiency was also achieved from integrated nutrients (50% FYM and 50% NPK) and irrigation at 50 mm PSMD. The results of this study have the potential to be expanded in arid and semi-arid areas where deficit irrigation is necessary to deal with water crises and to meet future food demands.

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