Potential soil moisture deficit: A useful approach to save water with enhanced growth and productivity of wheat crop

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ABSTRACT

Wheat is the main crop in the world ranks after rice and the largest grain source of Pakistan. Among several reasons for diminishing wheat yield in Pakistan, water stress throughout the growing season decreases crop production because of the short life span. Two years (2015–16 and 2016–17) of field experiments were conducted to assess the impact of various water regimes (full irrigation, irrigation at 45, 60, and 75 mm potential soil moisture deficit (PSMD)) on the growth and yield of wheat. Maximum crop growth rate was recorded by application of irrigation at 45 mm PSMD. Application of irrigation at 45 mm PSMD ensured maximum radiation use efficiency regarding total dry matter production and grain yield. The maximum number of productive tillers, spike length, and grain yield were recorded under 45 mm PSDM treatment. The present results show that the effect of water is more pronounced regarding the growth and productivity of wheat. Application of irrigation at 45 mm PSMD ensures higher economical yield.

Key words | dry matter, water deficit, wheat, yield

HIGHLIGHTS

- Physiological availability of water to plants is a key factor in crop production in the world.
- Potential soil moisture deficit (PSMD) is a useful approach to save water.
- Application of irrigation at 45 mm PSMD ensures higher economical yield.

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INTRODUCTION

Wheat is the largest grain source of Pakistan and ranks after rice as the main crop. It accounts for 80% of the cultivated area of about nine million hectares during Rabi season, therefore, it has an important role in formulation of new agricultural policies. Wheat flour is a key product with a big share of about 72% of Pakistan's everyday caloric consumption with per capita intake of about 124 kg/year, which is the highest in the world (Blackshaw *et al.* 2006; USDA 2017). The average yield of wheat crop in Pakistan is 2,827 kg ha^{-1} which is very low as compared to other countries (GOP 2020). In Pakistan, wheat yield could not achieve its maximum in comparison with different wheat producing countries in the world. Several ecological factors are responsible for limiting yield of crops (Bali & Sidhu 2020), and a small change in these from their normal array results in a decrease in plant growth and yield. Environmental variations result in numerous morphological, physiological, physiochemical, and molecular changes in plants. The world agriculture cereal production is also decreasing with climate change (Raza *et al.* 2019; Mubarik *et al.* 2021).

Pakistan has a good irrigation infrastructure, but climate change would result in inconsistency of the amount of water taken out at canal headworks and unpredictability in the frequency and intensity of rainfall. Furthermore, the average precipitation during July to September (monsoon season) is 138 mm, while in 2011–12 it received 237 mm precipitation which is more than normal precipitation. However, in the winter season of 2012, the amount of precipitation was 34 mm which was 51% less than the normal 71 mm, and consequently a decline in water amount taken out at canal headworks (GOP 2012). Hence, a decrease in canal water stores and unpredictability in precipitation are major threats to agriculture. The average need of water in rabi season (October to April) is $44.9 \times 109\ m^3$. However, severe scarcities of water will mean these requirements are not met (GOP 2012). Variability in precipitation is a burning issue for Pakistan, and it is a huge threat to the masses' food security in the long run. Water stress is a globally concerning issue and considered a complex hazard that directly influences the water balance of especially arid and semi-arid regions (Sur & Lunagaria 2020; Wang *et al.* 2020). Water shortage has a critical role in the final yield of crops (Holzman *et al.* 2018). Basal & Szabó (2020) reported that water stress is one of the most hazardous abiotic stresses that adversely influences crop yield. One of the national and universal concerns is to articulate different plans to manage existing water resources for agricultural use (Smith 2000).

For optimum growth and better yield of wheat recurrent irrigations should be applied because it is a rather sensitive crop to water stress (Alderfasi & Neilsen 2001). A better option or alternative is crop cultivation under a deficit irrigation scheme with less evapotranspiration to conserve water and other resources (Jalota *et al.* 2006). The ultimate objective of irrigation to crops is to meet water requirements and to boost the yield, in spite of the fact that water shortage is a severe issue for crop production in tropical areas owing to less or erratic rainfall patterns and climate change having a huge influence on tropical wheat production (Messmer *et al.* 2009). Irrigation water management is vital in all crops, especially in wheat because under- or overirrigation results in growth retardation of wheat and a decrease in yield. Most areas of Punjab often experience a dry weather environment, particularly during Rabi cropping season (Amin *et al.* 2020). Keeping in view the above discussion, the present study was planned (i) to evaluate the performance of wheat crop under different potential soil moisture deficit (PSMD) strategies and (ii) to explore PSMD as a helpful approach for irrigation scheduling in wheat.

MATERIALS AND METHODS

Crop husbandry

The present study was carried out at Agronomic Farm, Department of Agronomy, University of Agriculture, Faisalabad-Pakistan. Soaking irrigation (Rouni) was applied before the sowing of the crop to maintain soil moisture at field capacity (25% v/v) during the wheat crop growing season of 2015–16 and 2016–17. Wheat cultivar Sahar-2006 was sown using a seed rate of 100 kg ha^{-1} in rows 20 cm apart using a manual single row hand drill. Physio-chemical properties of the soil at the experimental site (Table S1) were analyzed before the crop was sown.

Recommended nutrient dose of N:P:K at 120:90:60 kg ha^{-1} was applied using urea, diammonium phosphate (DAP), and sulphate of potash (SOP) fertilizers as the source of nutrient. Nitrogen was applied in three equal parts, one-third of the total nitrogen was applied during seed bed preparation while the two remaining equal parts were applied at first and second irrigation. All phosphate and potash fertilizers were applied during seed bed preparation. Uniform weed management and plant protection measures were adopted throughout the experimentation cycle. Treatments included:

- Full irrigation/irrigation at all growth stages (control)
- Irrigation at 45 mm potential soil moisture deficit
- Irrigation at 60 mm potential soil moisture deficit
- Irrigation at 75 mm potential soil moisture deficit.

Before each irrigation, soil moisture percentage was determined by gravimetric method and depth of irrigation for the next irrigation was estimated as follows:

$$SMC\ (\%w/w) = ((W_w - W_d)/W_d) \times 100$$

where SMC = soil moisture content, W_w = weight of moist soil (as collected from the field at 45 cm depth), and W_d = weight of oven dried soil.

SMC (% on weight basis) was converted to SMC (% on volume basis) by the formula:

$$\text{SMC (\% on volume basis)} = \text{SMC (\% on weight basis)} \times \text{bulk density}$$

Depth of irrigation (D_i) was determined by the formula used by Fahad *et al.* (2019):

$$D_i = (FC - SMC)/100 \times BD \times D_r$$

where D_i = depth of irrigation (cm) or crop water requirement in depth (cm), FC = field capacity (% on volume basis), SMC = soil moisture content (% on volume basis), BD = bulk density (g cm^{-3}), and D_r = depth of root zone (cm).

A measured quantity of irrigation was applied according to the requirement (D_i) to replenish the depleted soil moisture using the equation:

$$T = AD_i/Q$$

where T = time in seconds for pre-determined amount of irrigation, A = area to be irrigated (m^2), D_i = depth of irrigation (m), Q = discharge of water channel at field head (flow of water through a point at m^3 sec^{-1}).

For measurement of discharge, a cutthroat flume was installed in the water channel and readings were observed at every irrigation. These readings were used to derive the water flow rate. The amount (mm) and date of irrigation are presented in Table 1. Data regarding prevalent weather condition throughout the crop season were obtained from a field meteorological laboratory situated in the vicinity of the experimental site (Figure S1).

Growth, yield and their attributes

To determine the growth parameters, each plot was divided into two sub-plots. One of them was used for destructive biomass sampling and the other half was kept intact for final grain yield measurements. From each plot, a 900 cm^2 area was harvested at ground level at intervals of every 15 days leaving appropriate borders. Fresh and dry weights of constituent fractions of the plant (leaf and stem) were determined. A sub-sample from each fraction was taken to dry in an oven to a constant weight. Crop growth rate was calculated as proposed by Hunt (1978):

$$CGR = (W_2 - W_1)/(t_2 - t_1)$$

where W_1 and W_2 are the dry weights harvested at time intervals of t_1 and t_2, respectively.

From the measurements of leaf area and dry weights the following parameters were calculated. Leaf area was

Table 1 | Date of irrigation water applied to crop during course of experimentation

	2015–16				2016–17				
Date	**I_1-C**	**I_2-45**	**I_3-60**	**I_4-75**	**I_1-C**	**I_2-45**	**I_3-60**	**I_4-75**	**Date**
12/09/2015	70				70				12/12/2016
12/16/2015		60				60			12/19/2016
12/16/2015			60				60		12/19/2016
01/06/2016	85			60	85			60	01/09/2017
01/27/2016		60				60			01/30/2017
01/30/2016	60				60				02/02/2017
02/08/2016			60				60		02/11/2017
02/22/2016	60	60		60	60	60		60	02/25/2017
03/09/2016	60	60	60		60	60	60		03/12/2017
03/16/2016				60				60	03/19/2017
Total (mm)	335	240	180	180	335	240	180	180	Total (mm)

I_1 = Full Irrigation/Irrigation at all stages (control), I_2 = irrigation at 45 mm potential soil moisture deficit, I_3 = irrigation at 60 mm potential soil moisture deficit, I_4 = irrigation at 75 mm potential soil moisture deficit.

measured by using a leaf area meter (Model CI-202, CID, Inc.). Five gram of leaf laminae from each experimental unit was used for the estimation of leaf area and then converted to total leaf area of harvested samples. Leaf area index (*LAI*) was then calculated as the ratio of leaf area to land area (Watson 1952):

$$LAI = \text{Leaf area}/\text{land area}$$

Leaf area duration (*LAD*) was estimated as suggested by Hunt (1978):

$$LAD = (LAI_1 + LAI_2) \times (t_2 - t_1)/2$$

Net assimilation rate (*NAR*) was determined according to Hunt (1978):

$$NAR = ATDM/LAD$$

where *ATDM* = final total dry matter and *LAD* = leaf area duration.

The fraction of intercepted radiation (*Fi*) was calculated from measurements of LAI using the exponential equation suggested by Monteith & Elston (1983):

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

where K = extinction coefficient for total solar radiation (Monteith & Elston 1983). A 'k' value of 0.45 was used for wheat.

The amount of intercepted light (*Sa*) was determined by multiplying *Fi* with incident *PAR* (*Si*) during the season as:

$$Sa = Fi \times Si$$

The photosynthetically active radiation (*PAR*) was assumed as 50% of the total incident radiation.

Radiation use efficiency for *TDM* (*RUE-TDM*) and grain yield (*RUE-GY*) was calculated as the ratio of total biomass and grain yield to cumulative intercepted *PAR* (Σ *Sa*):

$$RUE_{TDM} = TDM/\sum Sa$$

$$RUE_{GY} = \text{Grain yield}/\sum Sa$$

Water use efficiency (*WUE*) on *TDM* basis (WUE_{TDM}) and grain yield basis (WUE_{GY}) were calculated as the ratio of total biomass and grain yield to the total amount of irrigation applied and rainfall:

$$WUE_{TDM} = TDM/I + R$$

$$WUE_{GY} = GY/I + R$$

Fertile tillers per unit area, randomly selected from each experimental unit, were recorded manually at maturity. Ten plants were randomly selected from each treatment plot for measurement of plant height and spike length using a meter rod. The number of grains per spike and spikelets per spike were also counted manually. An electronic balance was used to record the 1,000 grain weight. Total wheat biomass was recorded with the help of a weighing balance. Grain yield from each plot was recorded by using an electronic weighing balance. Harvest index (*HI*) on a percentage basis was recorded for each treatment as ratio of grain yield to total biomass produced:

$$\text{Harvest index (\%)} = (\text{Grain yield}/\text{Biological yield}) \times 100$$

Statistical analysis

Data regarding all parameters were analyzed using Fisher's analysis of variance technique and the LSD test (least significance difference) was carried out at a probability level of 0.05 for comparison of variances among treatment means (Steel *et al.* 1997).

RESULTS

Growth, yield and their attributes

Crop growth rate (CGR) was significantly ($P < 0.05$) influenced by different irrigation regimes (Figure 1). The results showed that maximum CGR (9.98 g m^{-2} d^{-1}) was recorded by application of irrigation at 45 mm PSMD (Figure 1). Figure 2 depicts the effect of treatments on the fraction of intercepted radiation (Fi). The Fi reached a maximum value of 0.92 at 90 days after sowing, then it (0.61) gradually decreased up to maturity (Figure 2). Maximum net assimilation rate (NAR) was recorded under

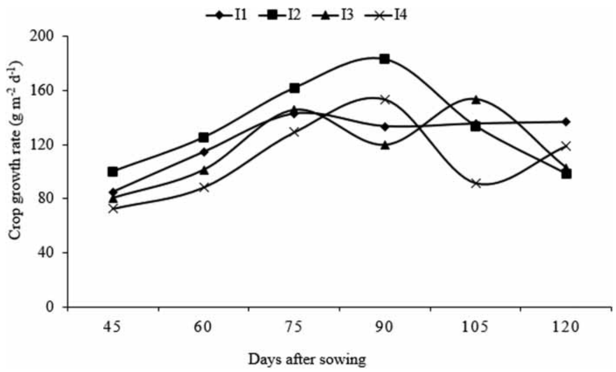

Figure 1 | Effect of deficit irrigation on crop growth rate of wheat. I_1 = Full irrigation/Irrigation at all stages, I_2 = irrigation at 45 mm potential soil moisture deficit, I_3 = irrigation at 60 mm potential soil moisture deficit, I_4 = irrigation at 75 mm potential soil moisture deficit.

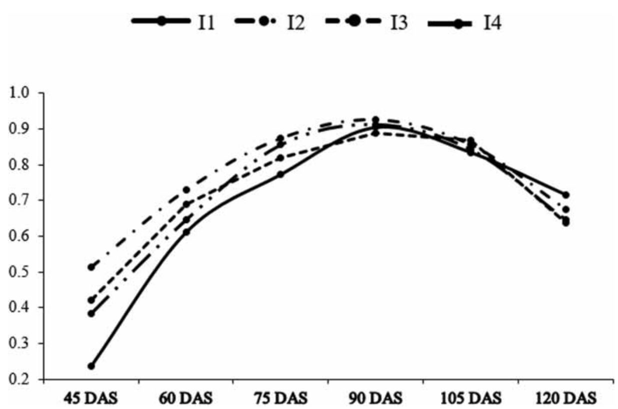

Figure 2 | Fraction of intercepted radiation (*Fi*) as affected by deficit irrigations. I_1 = Full irrigation/Irrigation at all stages, I_2 = irrigation at 45 = mm potential soil moisture deficit, I_3 = irrigation at 60 mm potential soil moisture deficit, I_4 = irrigation at 75 mm potential soil moisture deficit, DAS = Days after sowing.

irrigation at 60 mm PSMD with PAR under full irrigation regimes (Table 2). A significant difference was observed in water use efficiency (WUE) on total dry matter (TDM) and grain yield (GY) basis under different irrigation regimes (Table 2). Maximum value of RUE on TDM (3.94 g MJ^{-1}) and GY (1.18 g MJ^{-1}) basis was noted from wheat crop irrigated at 45 mm PSMD (Tables 2 and 3). Maximum tillers per unit area were recorded by irrigation at 45 mm potential soil moisture deficit (330 m^{-2}). The wheat crop, irrigated at 45 mm PSMD, resulted in maximum plant height (99.2 cm) (Table 3).

Application of irrigation at 45 mm PSMD resulted in maximum spike length of 14.3 cm. Spikelets per spike were observed to be maximum in the treatment where

Table 2 | Influence of irrigation regimes on net assimilation rate (NAR), photosynthetic active radiation (PAR), water use efficiency (WUE) by total dry matter (TDM) and grain yield (GY), and radiation use efficiency (RUE) by TDM

Treatments	NAR (g m^{-2} d^{-1}) 2015–16	NAR 2016–17	NAR Mean	PAR (MJ m^{-2}) 2015–16	PAR 2016–17	PAR Mean	WUE by TDM (g m^{-2} mm^{-1}) 2015–16	WUE by TDM 2016–17	WUE by TDM Mean	WUE by GY (g m^{-2} mm^{-1}) 2015–16	WUE by GY 2016–17	WUE by GY Mean	RUE-TDM (g MJ^{-1}) 2015–16	RUE-TDM 2016–17	RUE-TDM Mean
I_1	5.29	5.28	5.29B	600	598	599A	3.68	3.66	3.67D	1.19	1.17	1.18D	3.75	3.73	3.74B
I_2	5.20	5.18	5.19C	589	588	588B	5.19	5.21	5.20C	1.83	1.80	1.82B	3.95	3.93	3.94A
I_3	5.55	5.57	5.56A	582	581	582BC	6.37	6.42	6.39A	1.97	1.96	1.97A	3.67	3.67	3.67C
I_4	5.49	5.50	5.50A	577	576	577C	5.53	5.53	5.53B	1.63	1.64	1.63C	3.45	3.44	3.45D
Mean	5.38	5.37		587	586		5.19	5.21		1.65	1.64		3.71	3.69	
LSD	Y = ns, I = 0.0887, Y × I = ns			Y = ns, I = 6.0814, Y × I = ns			Y = ns, I = 0.0675, Y × I = ns			Y = ns, I = 0.0331, Y × I = ns			Y = ns, I = 0.0212, Y × I = ns		

Means sharing the same letter did not differ significantly at $P = 0.05$.
I_1 = Full irrigation/Irrigation at all stages (control), I_2 = irrigation at 45 mm potential soil moisture deficit, I_3 = irrigation at 60 mm potential soil moisture deficit, I_4 = irrigation at 75 mm potential soil moisture deficit, Y = sowing year, I = irrigation treatments, Y × I = interaction, ns = non-significant.

Table 3 | Influence of irrigation regimes on RUE by GY, number of tillers, plant height, spike length and number of spikelets per spike

Treatments	RUE-GY (g MJ^{-1}) 2015–16	RUE-GY 2016–17	RUE-GY Mean	Number of tillers (m^{-2}) 2015–16	Tillers 2016–17	Tillers Mean	Plant height (cm) 2015–16	Plant height 2016–17	Plant height Mean	Spike length (cm) 2015–16	Spike length 2016–17	Spike length Mean	Spikelets per spike 2015–16	Spikelets 2016–17	Spikelets Mean
I_1	1.07	1.08	1.08B	311	302	306B	94.0	93.3	93.7B	11.9	11.8	11.8B	16.3	16.2	16.3B
I_2	1.19	1.17	1.18A	334	326	330A	99.7	98.7	99.2A	14.1	14.5	14.3A	17.3	17.5	17.4A
I_3	0.97	0.96	0.97C	297	289	293B	89.4	89.9	89.7C	11.0	11.5	11.3C	15.1	14.9	15.0C
I_4	0.84	0.83	0.84D	259	251	255C	84.5	85.3	84.9D	10.4	10.2	10.3D	13.6	13.4	13.5D
Mean	1.02	1.01		300	292		91.9	91.8		11.9	12.0		15.6	15.5	
LSD	Y = ns, I = 0.0138, Y × I = ns			Y = ns, I = 22.120, Y × I = ns			Y = ns, I = 1.0651, Y × I = ns			Y = ns, I = 0.3433, Y × I = ns			Y = ns, I = 0.1870, Y × I = ns		

Means sharing the same letter did not differ significantly at $P = 0.05$.
I_1 = Full irrigation/Irrigation at all stages (control), I_2 = irrigation at 45 mm potential soil moisture deficit, I_3 = irrigation at 60 mm potential soil moisture deficit, I_4 = irrigation at 75 mm potential soil moisture deficit, Y = sowing year, I = irrigation treatments, Y × I = interaction, ns = non-significant.

wheat crop was irrigated at 45 mm PSMD (17.4), which was followed by the treatment which was irrigated at all growth stages of wheat (16.3) (Table 3). Maximum number of grains per spike (43) was observed in wheat crop irrigated at all growth stages, which was statistically similar to the treatment irrigated at 45 mm PSMD (42.1) (Table 4). Similarly, irrigation application at 45 mm PSMD produced maximum 1,000 grain weight (44.3 g) followed by the treatment irrigated at all growth stages (41.6 g). Maximum grain yield was observed in the wheat crop by application of irrigation at 45 mm PSMD. The biological yield was observed as maximum under the treatment which received irrigation at 45 mm PSMD (12,908 kg ha^{-1}). Wheat crop, irrigated at a moisture deficit of 45 mm PSMD, resulted in maximum harvest index (30.08%) (Table 4).

CORRELATION AND REGRESSION ANALYSIS

The relationship between different growth and yield parameters is calculated and presented in Figure 3. The relationship between crop growth rate and total dry matter was recorded as linear and was strongly positive giving an R^2 value of 0.95. Regression relation of the

Table 4 | Influence of irrigation regimes on number of grains per spike, 1,000-grain weight, grain yield, biological yield and harvest index

Treatments	Grains per spike			1,000 Grain weight (g)			Grain yield (kg ha^{-1})			Biological yield (kg ha^{-1})			Harvest index (%)		
	2015–16	2016–17	Mean	2015–16	2016–17	Mean	2015–16	2016–17	Mean	2015–16	2016–17	Mean	2015–16	2016–17	Mean
I_1	43.3	42.7	43.0A	41.8	41.5	41.6B	3,511	3,493	3502B	12,284	12,272	12,278B	28.58	28.46	28.52B
I_2	42.6	41.7	42.1A	44.5	44.2	44.3A	3,881	3,885	3883A	12,900	12,916	12,908A	30.09	30.08	30.08A
I_3	40.2	41.7	40.9B	37.5	37.2	37.4C	3,177	3,164	3171C	12,103	12,099	12,101C	26.25	26.15	26.20C
I_4	37.7	36.3	37.0C	35.6	35.3	35.5D	2,806	2,792	2799D	11,349	11,329	11,339D	24.72	24.65	24.68D
Mean	41.0	40.6		39.9A	39.5B		3344A	3334B		12,159	12,154		27.41A	27.34B	
LSD	Y = ns, IM = 0.9471, Y × I = ns			Y = 0.226; I = 0.319, Y × I = ns			Y = 7.301; I = 10.32, Y × I = ns			I = 8.2864, Y × I = ns			Y = 0.066; I = 0.093, Y × I = ns		

Means sharing the same letter did not differ significantly at $P = 0.05$.
I_1 = Full irrigation/Irrigation at all stages (control), I_2 = irrigation at 45 mm potential soil moisture deficit, I_3 = irrigation at 60 mm potential soil moisture deficit, I_4 = irrigation at 75 mm potential soil moisture deficit, Y = sowing year, I = irrigation treatments, Y × I = interaction, ns = non-significant.

number of productive tillers with grain yield was positive and linear giving R^2 values of 0.80. The spike length had a good positive and linear relationship with grain yield, and the R^2 value was 0.96. Number of grains per spike gave a regression value of 0.84 in relation to grain yield. The relationship between grain yield and harvest index was linear and positive, and gave a regression value of 0.84. The regression relation of radiation use efficiency with grain yield was strongly positive and linear, and the value of regression was 0.99 (Figure 3).

DISCUSSION

Appropriate irrigation frequency and intensity is a critical factor for the optimum production of field crops. Various irrigation regimes significantly affected the growth and yield contributing parameters of wheat crop. Irrigation water management is vital in all crops, especially in wheat because under- or overirrigation resulted in growth retardation of wheat and a decrease in yield. A better option or alternative is crop cultivation under a deficit irrigation scheme with less evapotranspiration to conserve water and other resources (Jalota *et al.* 2006). In the present study, application of irrigation at 45 PSMD produced the maximum yield and was found more responsive regarding the growth and yield of wheat crop. Zhang *et al.* (2004) stated that soil water deficit played a significant role in crop production. Their findings are in line with outcomes of the present experimentation. They stated that severe soil water deficit significantly reduced the economical yield of wheat crop as compared to slight soil water deficit. They also stated that evapotranspiration of crop also depended on irrigation amount. Qiu *et al.* (2008) also observed WUE on the basis of photosynthesis and biomass production and found a positive correlation between WUE and winter wheat grain yield. Application of irrigation at 45 mm PSMD produced the highest grain yield and its components in the present study. These outcomes are also supported by Bashir *et al.* (2016). PSMD at 45 mm was found to be the most appropriate throughout the experimentation because it appears responsible for maximum plant height, number of grains per spike, thousand grain weight, productive tillers, and economic yield.

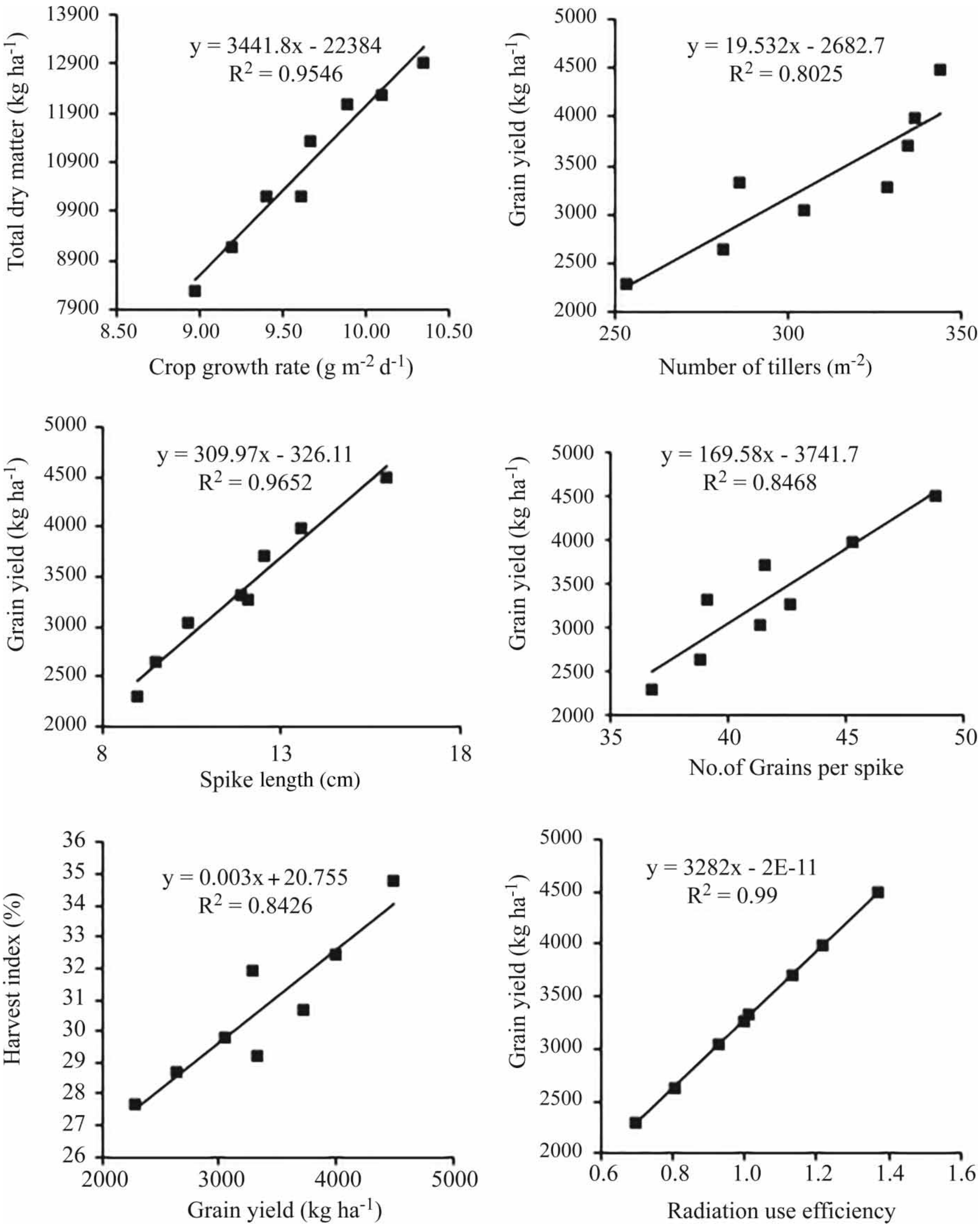

Figure 3 | Co-relation among various attributes of wheat cultivated under different irrigation regimes.

The current study results revealed that deficit irrigation at 45 mm PSMD is more water-saving than conventional practices of irrigation of traditional farmers. The consequences of the current experiment are comparable with the findings of Li *et al.* (2005), who found that the highest number of tillers were observed when wheat crop was irrigated at critical growth stages and the least number of tillers when irrigation was applied at longer intervals. Application of water deficit irrigation at 45 PSMD produced taller plants comparatively, as recorded in the present study. The reason for taller plants might be the application of irrigation at all crucial stages, i.e., tillering, elongation, booting, anthesis and grain development stages, while similar plant height attained when irrigation at grain filling stage was skipped was due to the fact that the vegetative growth stage of the plant was completed at that stage. Shorter plants developed when irrigation was skipped at tillering and anthesis stage which resulted in lack of adequate moisture for stem elongation. Plant height was favored as irrigation was provided to wheat crop at all critical stages of crop growth (Qiu *et al.* 2008). Kazemi *et al.* (2021) also reported that water stress was responsible in the significant reduction of yield attributing traits.

Water deficit conditions resulted in the reduced number of grains per spike as well as in productive tillers per unit area in wheat crop (Sayyah *et al.* 2015). Our results are in agreement with Moayedi *et al.* (2010) and Plaut *et al.* (2004), who reported reduced 1,000 grain weight and grain yield in wheat due to water deficit during grain filling stage. According to Shehzad *et al.* (2012), more grain weight was recorded under 50 mm PSMD treatment, and increasing the water deficit level up to 75 mm PSMD significantly reduced the grain weight. A similar trend of 1,000 grain weight was found in relation to deficit irrigations in the current study. Salsinha *et al.* (2021) stated that water stress affected various growth parameters negatively which ultimately reduced the economic yield.

The correlation between productive tillers and grain yield is of prime importance (Figure 3). A positive correlation between the number of productive tillers and grain yield was observed in wheat under drought stress conditions (Mohammadi *et al.* 2011). Our findings of positive correlation between productive tillers and grain yield are also in line with the results of Peymaninia *et al.* (2012) and Chalabi & Rashidi (2012). Taiz & Zeiger (2006) reported that measurement of biomass is the key factor to determine drought stress in plants. Therefore, biomass has a pivotal role in increasing grain yield. A positive correlation between grain yield and harvest index was observed (Figure 3). The study of Kirigwi *et al.* (2004) supports our findings as it reported a positive correlation of grain yield with biological yield and harvest index in varying water deficit levels. The current study results revealed that deficit irrigation at 45 mm PSMD is more water-saving than conventional practices of irrigation of traditional farmers. PSMD at 45 mm is also found most appropriate throughout the experimentation because it appears responsible for maximum plant height, number of grains per spike, 1,000 grain weight, productive tillers, and economic yield.

CONCLUSION

The physiological availability of water to plants is a key factor in crop production throughout the world. Data suggest that there is still huge scope to increase wheat grain yield by using deficit irrigation sensibly. Under a climate change-induced water shortage scenario, lack of adequate moisture at early growth stages has a more detrimental effect than at later growth stages. Maximum growth and yield of wheat crop in the field can be achieved by applying irrigation at 45 mm PSMD. Hence, irrigation at 45 mm PSMD is suggested for achieving high productivity.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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