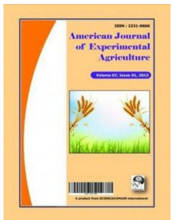

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Root Morphology and Yield of Wheat (*Triticum aestivum* L.) Crop under Reduced Irrigation in Delhi (India) Weather Conditions

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Authors' contributions

This work was carried out in collaboration between all authors. Author AKM designed the study, wrote the protocol and wrote the first draft of the manuscript. Author SSP reviewed the experimental design and all drafts of the manuscript. Authors TKS and VVK managed the analyses of the study. Author VVK took the field measurements of certain parameters, laboratory analysis. Author KC helped in various field operations and maintenance of the experiment, helped the scientists in data collection by identifying the plants. Authors AKM and SSP performed the statistical analysis. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Water is one of the most valuable resources for the survival of civilization. Assured supply of water is necessary for sustainable agriculture. Wheat (*Triticum aestivum* L.) is an important staple food crop in India and is cultivated in different agro-ecological regions of northern, eastern and central parts of the country occupying 25.4 million hectare (M ha) and nearly 54% of its area is irrigated. A sizeable 46% area under wheat is still rain dependent which often is faced with reduced irrigation thus decreased crop yield. The aim of this study is to facilitate the farmers of this reason in taking the appropriate decisions as regards providing supplemental irrigation with limited water supply conditions so that comparable yields could be obtained with the water application to critical crop growth stages.

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That constitutes about 27% of the irrigated area of India. Changing climate has resulted into recurrence of long rainless spells during winter season (rabi) at places in India known for extensive wheat production which is main staple food of the masses. Wheat crops growth and performance is adversely affected by soil moisture stress so is the growth of roots and consequently the nutrient uptake that reflects into the yield and yield attributes. Hence, the main objectives of present study were to access, the effect of reduced irrigation on yield attributes, root development, dry matter accumulation and partitioning of wheat (*Triticum aestivum* L.) crop under reduced irrigation in Delhi (India) during winter (rabi) weather conditions.

Study Design: Randomized Block Design (RBD) with four replicates.

Place and Duration of Study: Field experiments were conducted at the W-3 Experimental Farm of the Water Technology Centre, IARI, New Delhi during the rabi cropping season of 2011-12. Indian Agriculture Research Institute (IARI) is located at New Delhi (28º38'N, 77º10'E) at an elevation of 248 m above MSL. The crop was sown in the month of Novemebr and harvested at the end of April of the next year. The sandy loam soils of the experimental area, where the field experiments were conducted can be characterized as having low water holding capacity. Delhi falls in the semi arid climatic conditions. The experimental design for the experiment was Randomized Block Design (RBD), replicated four times. The present experiment used a high yielding cultivar of wheat variety HD 2967 having the growth period of 120 days.

Methodology: For root analysis, the roots were taken from a depth of 0-90 cm and were analyzed for different properties like root length, surface area and volume using root scanner (EPSON expression 1640XL, Japan). The same roots were then used for measuring wet mass and kept in an oven at 70ºC for three days before taking dry mass (Figs. 3 and 4). WinRhizo^{TM} software was used with an approved scanner, Yield and yield attributes were measured using standard experimental procedures. Observations on plant growth (crop morphometry, photosynthetic activity (LAI), dry mass partitioning), soil moisture dynamics and yield of wheat *(Triticum aestivum* L.*)* crop were taken under a well structured schedule.

Results: There was no significant difference in the plant height in the early stages (30 days after sowing (DAS)) in wheat during the winter (rabi) season of 2011-12. However, in the later stages i.e., during late vegetative and reproductive phases, various treatments exhibited significant differences in yield and yield attributes. Also, in number of tillers/m^2 and leaf area index (LAI) a highly significant differences were observed among treatments. It was worth noticing that skipping irrigation in CRI and milking stages has significant decrease in the dry matter accumulation even though the treatment with no water deficiency (T8) recorded highest dry matter accumulation. Significant differences among the treatments were also observed especially in root length. The treatment T1 with no irrigation (Control) recorded in significant reduction with T8 treatment (no water deficiency), which clearly indicated that root of the crop elongated in stress condition to fulfill its metabolic activities. crop tries to utilize the available soil moisture in this case. Root length has also shown a direct correlation with soil moisture availability.

Conclusion: Skipping of irrigation during tillering stage has drastically reduced the elongation of root among all the treatment. T4 treatment (100% soil moisture deficient at booting stage) has resulted in highest root length which indicates that irrigation is critical during the flowering and milk stages of wheat. Root surface has been drastically reduced in treatment T1 (No irrigation in all growth stages).

Keywords: Rainfall; reduced irrigation; leaf area index; irrigation; root morphology; root biomass; wheat (Triticum aestivum L.) crop; water Management.

1. INTRODUCTION

Water is one of the most valuable resources for the survival of civilization. Assured supply of water is necessary for sustainable agriculture. Wheat (*Triticum aestivum* L.) is an important staple food crop in India and is cultivated in different agro-ecological regions of northern, eastern and central parts of the country occupying 25.4 million hectare (M ha) and nearly 54% of its area is irrigated. That constitutes about 27% of the irrigated area of India [1]. The agriculture sector is the largest consumer of water resources in Indo-Gangetic plains which is the main cereal producing area in India. Well-drained clay loams, loams and sandy loams are suitable for this crop. The majority of farmers of

Indo-Gangetic plains are using water irrationally [2,3]. Wheat production in India generally happens in cooler month (winter season) where there is limited water loss from the soil surface. Due to increased cropping intensity water is becoming a limiting factor in wheat production areas in India [4,5]. Hence, the yield and quality of wheat (*Triticum aestivum* L.) crop often suffers due to insufficient water supply and improper scheduling of irrigation [6-8]. Again, excessive irrigation under shallow water table condition especially in lower portions of the Indo-Gangetic belt, will not only aggravate the problem of water logging but will also reduce the irrigated area and total yield [9-11]. The appropriate crop water requirement (CWR), critical crop growth stages and irrigation schedules are highly essential for realizing targeted level of crop production. The appropriate water amount, its time of application (schedules) are vital for optimal water productivity of any crop [12].

Crop water use varies substantially during the growing period due to variation in crop canopy and climatic conditions [13]. Total crop water use is nothing but the sum of root water uptake plus soil evaporation plus interception, and the spatial and temporal pattern of soil water use by crops can best be obtained from the accurate profile description of hydraulic conductivity, soil water flux and rooting pattern [14]. Field water balance is commonly used to measure total water use or actual crop evapotranspiration (ET_a) when lysimeter facilities are not available and it is found that ET_a increases with the increase in number of irrigation from one to adequate [15]. The prediction of ET_a and crop coefficients (K_c) as a function of growth period is very much important for determining crop water use and scheduling irrigation at a regional level [13]. Under stress conditions, ET_a is calculated by the combining effect of K_c and soil water stress coefficient (K_s).

In India the location specific crop coefficients (K_c's) have not been worked out for many crops. Hence, for irrigation scheduling based on the estimation of crop water requirements all the researchers invariably use the FAO CROPWAT-56 data for K_c [13]. The experimental verification being tedious, time consuming and difficult; many attempts have not been made in the past to experimentally verify the results of such arbitrary assumption [1,16].
Much is known about the CWR of wheat using field water balance and/or lysimeter study in field experimental plots at various agro-ecological conditions of India [2,17,18]. Therefore, the thorough knowledge of optimum time and amount of limited water to be applied to obtain higher productivity is essential. Under normal conditions, four-to-six irrigations were recommended for optimum wheat production in India [19-24].

Much is known about the CWR of wheat using field water balance and/or lysimeter study in field experimental plots at various agro-ecological conditions of India [2,17,18]. Therefore, the thorough knowledge of optimum irrigation schedules for realizing higher crop and water productivities are a must. For obtaining optimum water productivity in wheat crop the researchers have advised a minimum of four and a maximum of six irrigations [19-24]. Several researchers have already made crucial attempts to identify the critical crop growth stages corresponding to Indian weather conditions in wheat crop [25-27,87] that has resulted into a clear understanding of water sensitive growth stages for applying irrigation.

When water becomes scarce, demand management becomes the key to the overall strategy for managing water [28]. All the available residual soil moisture can be used by a crop since dry soil conditions promote root elongation and branching [29]. Hence, most of the residual soil water in the soil profile can be utilized. Water deficit has become a leading environmental constraint that limits crop photosynthesis, productivity and yield [6,30,31]. A decline of photosynthesis in water stressed plants can be caused by stomata closure and impairments in photochemical and/or biochemical reactions [32,33]. Water deficit also results in increase dry matter allocation to roots [34,35] which can enhance water uptake [36]. Roots, in wheat crop comprise close to half total plant biomass [37] and are critically involved in water up take and nutrient supply. Deeper roots can extract more water from depth thus avoiding water deficits at critical growth stages resulting in higher harvest indices and reduced water loss by deep drainage [38,39] studied the effective management of irrigation water for wheat crop under stressed conditions using simulation modeling. It was concluded that under water scarcity condition, when soil water stress is imposed during non-critical stages of growth, irrigation is to be scheduled at 45% maximum allowable depletion of available soil water for wheat crop grown in sandy loam soils in subhumid regions in order to obtain maximum grain yield and above ground dry matter. Also, in order to obtain the highest water use efficiency (WUE), irrigation is to be scheduled at 45% Maximum Allowable Depletion (MAD) of available soil water for wheat crop in sandy loam soil. However, increased early vigour leads to faster, deeper root growth and more adventitious roots in the top soil thus improving water and nutrient use and reducing evaporative losses from the top soil [40,41]. Generally, 70% of the total root volume is found in the top 0-30 cm soil layer, where most nutrients are present in the majority of the agricultural soils [42]. The existing root length density of wheat is not sufficient to extract all the available water deep in the soil profile [43,44].

Further, the grain yield in *rabi* (winter) wheat (*Triticum aestivum* L.) is influenced not only by shoot characteristics, morphological traits such as plant height and number of tillers, and phonological periods such as time to anthesis and maturity. Information on the relationship between grain yield but also the root characteristics, such as root morphology, root biomass and shoot biomass in wheat [12,45-48]. It was reported by [49] that water stress during tillering until physiological maturity causes significant reduction of wheat grain yield cultivars. Also, this reduction results from both grain weight reduction and number of grain per spike. In a controlled research, [50] reported the 25 and 50% reduction of water consumption may decrease grain wheat yield 21.8% and 40.7% respectively. In another experiment, [51] also reported that different irrigation treatments have significant effect over wheat protein index; therefore, the increase in water stress would lead to grain protein percentage rise in all cultivars. They report that the decrease in moderate and intense stresses would bring a drop in grain yield 23% and 46% respectively. The increase in water use leaded to increase of 1000- grain weight in cultivars was reported by [52]. It should be also taken into consideration that different genotype behaves differently in water stress condition. Genotypic variations related to photosynthetic activity, productivity and grain yield under water deficit has also been extensively reported [53]. Therefore, proper management of important inputs particularly irrigation water using modern technology is essential for increasing production and for giving high return to the farmers. Crop growth simulation models could be used as useful tools for determining crop growth, development and to formulate irrigation management strategies for efficient use of inputs [54,55].

Despite their crucial role of roots in realizing higher production; very little attention has been paid to the study of root morphology, traits and root biomass as compared to more easily assessable above ground (shoot traits). Drought is the most common crop stress globally and characters that improve water-use-efficiency (WUE) such as sub-soil water extraction by roots can be enhanced through agronomic management or plant breeding to increase yield. However, the benefits depend on the seasonal pattern of water availability as influenced by rainfall distribution, soil type and management [56]. Under soil water deficit conditions therefore, the crop water extraction depends on root distribution and depth [57]. As a result to enhance the food security and taking into the local and global water scarcity conditions into consideration, the present study was conducted with wheat variety HD 2967 for studying the effect of soil moisture deficit during different crop growth stages on root and shoot growth (root morphometry and root dynamics and photosynthetic activity (LAI)), soil moisture dynamics, and grain yield of wheat (*Triticum aestivum* L.) crop. Apart from these an analysis of the water dynamics would also enabled to apply the precise amount of water to the crop root zone to avoid the deep percolation losses which accounts for the maximum wastage during the irrigation.

The deep percolation losses accounts for the maximum wastage during the irrigation which can also be attempted by analysis of the water dynamics apart from all the above mentioned parameters which can result into an application of the precise amount of water to the crop root zone to avoid the losses. The results of the present study would not only help the farming community of Delhi NCR region in significant amount of water saving during the entire crop growth season of *rabi* (winter season crop) but also help in reallocating the balance amount of water for bringing more areas under irrigation.

2. MATERIALS AND METHODS

2.1 Experimental Site

The Indian Agriculture Research Institute (IARI) is located at New Delhi (28º38'N, 77º10'E) at an elevation of 248 m above MSL. For accessing the effects of reduced irrigation on soil moisture, root dynamics, yield and water productivity of wheat crop *(Triticum aestivum* L.) crop the field experiments were conducted at WTC farm No.3. During the winter season of the year 2011-12, the field investigations were carried out with wheat variety HD2967 (duration 120 days) in sandy loam soil in Randomized Block Design (RBD), replicated four times and eight different treatments of with an objective to identify the most critical crop growth period corresponding to the ambient weather conditions most adversely affecting the crop during the limited irrigation.

The eight treatments were decided in such a manner that moisture limiting stages can be easily identified against the control (i.e complete soil moisture deficit meaning absolutely no post sowing irrigation). Other treatments were; complete soil deficit during crown root initiation (CRI) stage; complete soil moisture deficit during the tillering stage (TS); complete soil moisture deficit during booting stage (BS); complete soil moisture deficit during flowering stage (FS); complete soil moisture deficit during milking/dough stage (DS); complete soil moisture deficit during grain filling stage (GFS); and fully irrigated in all growth stages (providing irrigation in all the crop growth stages) i.e. absolutely no deficit in any stage having ample soil moisture in all growth stages).

Further bifurcation of the growth stages were avoided due to the limitations of the field, facilities and manpower. The seeds of wheat variety HD 2967 were machine sown at a distance of 22 cm row to row spacing. The basal dose of the fertilizers (NPK) was applied at the rate of 140:60:40 kg/ha [58] based on the previous results of soil analysis. The area of the each experiment plot was 36 m^2 (6mX6m) leaving a buffer strip of width of 1.5 m between two adjacent plots which provided the much required buffer to avoid the seepage of irrigated water across different plots. The crop was irrigated based on the soil water availability. During the entire experimental period, the crop could receive rainfall only once (recorded to be 5 cm). The structured details of all the treatments are given below:

2.2 Treatment Details

The field experiment in winter (Rabi) season 2011-12 was conducted with following eight treatments T1 - Control (Pre-sowing+No irrigation in all growth stages) T2 – No irrigation during CRI stage; T3 – No irrigation during tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages There were three replicates in 36 sq. m. plot size with row to row spacing of 22.5 cm. The crop was sown using a seed drill machine in RBD experimental design with full doses of P & K and half dose of N as basal @ N:P:K:: 120:60:60 on 11.11. 2011, with wheat variety Pusa HD 2967 and harvested on 29th April, 2012.

2.3 Field Sampling of the Roots and Image Analysis

2.3.1 Root auger and root scanner

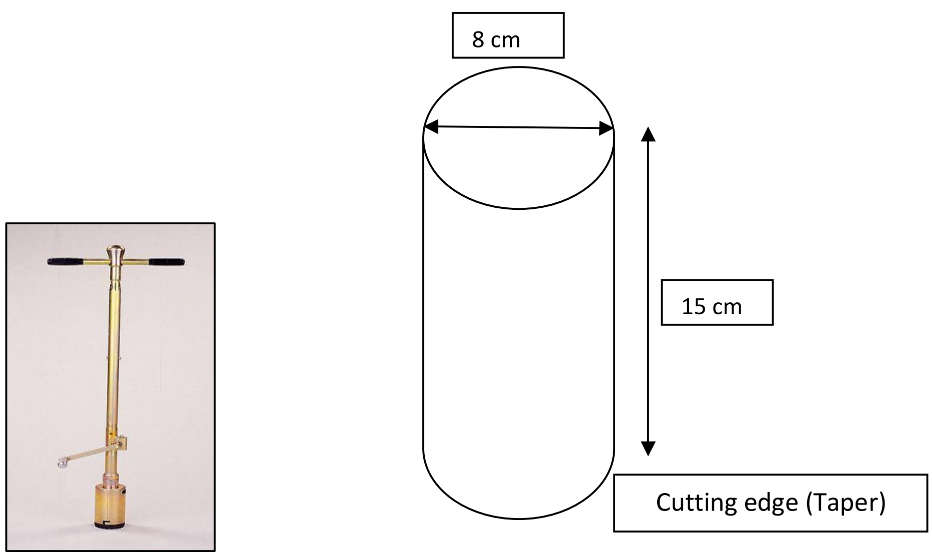
Root sampling was done using soil core method with the help of soil auger at different vegetation stages and soil depths (15-90 cm). Roots were washed properly and collected on a sieve with 0.5 mm mesh screen. Debris and dead roots were manually removed from vital roots by considering their color and flexibility. The auger body (Fig. 1) consists of a steel cylinder holding an exchangeable, toothed drilling-crown. The drilling crown is made from hardened steel and its toothing allows cutting through the rooted soil. The top end of the cylinder is closed and has a breather hole. The auger body is sturdy and as such suitable for use in hard soils. The cylinder's diameter is 8 cm, its operational depth is 15 cm and its volume is 753.60 cm^3. Roots are floated in water in acrylic trays on the scanner (Fig. 2). This allows the roots to be arranged to reduce overlap and crossing of roots. For root analysis, the roots were taken from a depth of 90 cm and were analyzed for different properties like root length, surface area and volume using root scanner (EPSON expression 1640XL, Japan). The same roots were then used for measuring wet mass and kept in an oven at 70ºC for three days before taking dry mass (Figs. 3 and 4). WinRhizo TM software was used with an approved scanner, which allows the roots to be lit from above and below while being scanned (Fig. 3). Measurements involved total root length, average root diameter, projected and surface area, plus length and area measurements as a function of different root diameter classes. The images were saved as gray scale image as given below. Analysis of the image is a very important step. Even though WinRhizoTM can automatically set these, but we need manually tweak them from time to time. If the roots are voluminous the smaller region of the image should be analyzed for clarity. The color traces on the root indicate where roots have been detected. The output results are given ready for analysis [58].

2.4 Leaf Area Index (LAI) and Dry Matter Partitioning (DMP)

The gravimetric method [50] was employed for field measurement of soil moisture and its dynamics. Soil samples from four different depths (0-15, 15-30, 30-45 and 45-60 cm) were collected from the field and the soil moisture content was estimated using gravimetric method. A Laser leaf area meter (model: CI-203) was used for estimating the leaf area index. Since this instrument requires more time to estimate the leaf area; only representative samples were analyzed with the same. LAI for the remaining stages of the crop were computed by length and breadth method (using crown leafs of five plants and taking their average length and widths). A correction factor of 0.65 was multiplied as suggested by [59] in the average leaf area estimated by initial measurements. Five (5) representative plants were taken to study the dry matter production in each stage for estimating the dry matter partitioning.

2.5 Field Scout Digital Moisture Sensor

The Field Scout Digital Moisture Sensor allowed us to monitor and record soil moisture quickly and accurately. The Field Scout Digital Moisture Sensor having two volumetric water content modes; one for standard soils and one for higher clay soils with TDR technology (time-domain measurement technology was used for measuring the soil moisture and validated with gravimetric method by constructing a calibration chart. The meter converts a measured electrical signal into % soil moisture content using an equation valid over a wide range of mineral soils in volumetric water content (VWC) mode. However, In irrigation mode, the meter displays relative water content (RWC) on a scale of 0 to 100 corresponding to a user-defined upper and lower soil moisture reference level. It is fitted with two 3.8 cm rod, two 7.5 cm rod, two 12 cm rod, and two 20 cm rod [60].



a. Root Augur assembly with core sampling mechanism

b. Root Augur core sampling mechanism showing the dimensions

Fig. 1. Root auger
Source: http://pkd.eijkelkamp.com

Fig. 2. The root morphology analysis using Root Scanner (EPSON expression 1640XL, Japan)

Fig. 3. A sample grey scale image (*.TIF image) of wheat crop roots

2.6 Field Measurement of Yield Parameters

For estimating yield parameters, twenty ear heads selected at random from each plot at harvest were used for recording the grain weight per ear head in g. The net plot was marked, harvested separately and total biomass yield from each net plot was recorded. After threshing, grains were separated, cleaned and weighed. Straw yield per net plot was worked out by subtracting respective total grain weight from the total biomass yield. Later the grain and straw yield per net plot was computed on hectare basis and expressed in q per ha. Harvest index was calculated [7] by using formula of as: HI = EY/BY and HI = GY/TBY; where, HI = Harvest Index (q/ha); EY= Economic yield (q/ha); BY = Biological yield; (q/ha) GY=Grain yield (q/ha) and TBY= Total biomass yield (q/ha). The analysis of the above ground biomass and the average grain weight per spikelet (gm) (average of 20 spiklets) has been presented and conclusions have been drawn on the basis of information so obtained.

3. RESULTS AND DISCUSSION

3.1 Analysis of Root Morphology

Several researchers [9,39] have hypothesized that the ability of a plant to change its root distribution in the soil is an important mechanism for drought avoidance. Different patterns of root growth were observed in treatments with different soil water regimes [10,40].

3.2 Effect of Irrigation Treatments on Root Length (cm) of Wheat (*Triticum aestivum* L.) Crop under Reduced Irrigation at Delhi Weather Conditions

The treatment and replication wise root lengths of wheat (*Triticum aestivum* L.) crop under reduced irrigation after 70 DAS and 100 DAS are presented in Table 1 wherein the mean root lengths have also been worked out. It was observed that after 70 DAS the minimum root growth of only 931.06 cm was recorded in T5 (i.e – No irrigation during Flowering stage) followed with T3 (i.e. – no irrigation during Tillering stage); in which the total root length was 1001.45 cm. The maximum root development and growth (1920.06 cm) was observed in treatment T4 (i.e–no irrigation during booting stage); preceded by T2 (1512.79 cm) (i.e. no irrigation during CRI stage). Whereas, in case of 100 DAS, the highest root growth of 2715.32 cm was recorded in the treatment T6 (no irrigation milk/dough stage); followed with 2456.24 cm in T7 which is no irrigation during grain filling stage. The Post-hoc analysis was done as suggested by [60] and is presented in Table 2. On persuasion of both these (Tables 1 and 2) it is clear that the root lengths were significantly affected by the reduced levels of soil moistures in different treatments that coincided with the crop sensitive stages in varying degrees. In Table 2, where means with the same letter are depicted as being not significantly different; one can easily notice that soil moisture deficit has not very clear cut distinction among the treatments but is indicative only. While the soil moisture deficit in certain stages have nominal effect on crop root growth inferred by the way of non significant mean differences after 70 DAS. On the contrary, in the later stages of the crop development when the crop completed its full growth potential and neared maturity the effective soil moistures deficits have altogether changed scenarios. After 100 DAS the minimum root growth was observed in treatment T3 (1275.57 cm) (i.e. no irrigation during Tillering stage) followed with T5 once again with 1648.39 cm. This clearly confirms that T5; i.e. no irrigation during flowering stage can seriously hamper the root growth pattern. However, various treatments showed significant difference in mean root lengths after 70 and 100 DAS with non-uniformity and a few showed no significant difference (Table 2). A closer look of Fig. 5 and Fig. 6 will support this fact because while the soil moisture has been imposed among various treatments there has been a few good showers during the winter season that might have replenished the root zone soil moisture which is evident from Fig. 2 too. These results are in strict agreement with the findings of some of the past researchers [40,76-78]. The functional relationship developed between the number of days after showing and root length (cm) for all treatments at two stages (70 DAS and 100 DAS) have been worked after fitting the most appropriate trend lines and are given below with their respective R^2 (eqn. 1 & 2). Functional relationship between number of days after sowing and the root length for:

Fig. 4. A sample Win Rhizo™ analyzed image of wheat (*Triticum aestivum* L.) crop roots

3.2.1 Functional relationship between number of days after sowing and the root length 70 das

A sixth order polynomial between Number of Days after Sowing and the Root Length (70 DAS) of the type below; was fitted and the value of R^2 was worked out:

$$y = -2.94x^6 + 79.68x^5 - 844.6x^4 + 4430.x^3 - 11975x^2 + 15591x - 6147 \quad (1)$$

$R^2 = 0.255$

3.2.2 Functional relationship between number of days after sowing and the root length 100 das

A sixth order polynomial between Number of Days after Sowing and the Root Length (100 DAS) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = -2.390x^6 + 68.73x^5 - 783.6x^4 + 4457.x^3 - 12964x^2 + 17508x - 6077 \quad (2)$$

$R^2 = 0.465$

R^2 values in both the functional relationships (eq. 1 & 2) are not very encouraging that supports the statement made as above regarding the root growth patterns after 70 and 100 DAS. It can be seen from these values that after 70 DAS till the 100 DAS the plant responded in a much balanced manner as regards to plant root length than 70 DAS which showed an indefinable/ zig-zag pattern.

3.3 Effect of Irrigation Treatments on Root Surface Area (Cm^2) of Wheat (*Triticum aestivum* L.) Crop

The treatment and replication wise root surface area of wheat (*Triticum aestivum* L.) crop under reduced irrigation after 70 DAS and 100 DAS are presented in Table 3 wherein the mean root surface area have also been worked out (Table 3). It was observed that after 70 DAS the minimum root surface area of only 174.61 cm^2 was recorded in T7 (i.e 100% soil moisture deficit during grain filling stage) followed with 265.71 cm^2 in T2 (i.e. – 100% soil deficit during CRI stage). The maximum root surface area (400.71 cm^2) was observed in treatment T4 (i.e–no irrigation during booting stage); preceded by T8 (331.79 cm^2) (i.e. no deficit (providing irrigation in all the stages) which is quite obvious too.

Whereas, in case of 100 DAS, the highest root surface area of 411.25 cm^2 was recorded in the treatment T7 (100% soil moisture deficit during grain filling stage); followed with 401.48 cm^2 in T6 which is 100% soil moisture deficit during milk/dough stage. The Post-hoc analysis is presented in Table 4. On persuasion of Tables 3 and 4 it is quite clear that the root surface area were significantly affected by the levels of treatments though a definite trend as per the treatment details could not be established from the data of root surface area of various treatments. However, a clear cult idea about root surface area emerged as the moisture sensitive stages are also equally sensitive to root development and root surface area. In Table 4, where means with the same letter are depicted as being not significantly different one can easily notice that soil moisture deficit has not very clear cut distinction among the treatments but is indicative (Fig. 7). As explained in section 3.1.1; the root length as well as root surface area might have experienced the similar stress conditions and the trend (Fig. 7) is almost similar. While the soil moisture deficit in certain stages have nominal effect on crop root surface area inferred by the way of non-significant mean differences after 70 DAS (Tables 3 and 4). Similarly, at a later stage of the crop development when the crop completed its full growth potential and neared maturity the effective soil moistures deficits have altogether changed scenarios. After 100 DAS the root surface area was observed to be at a minimum in treatment T1 (complete soil moisture deficit in all growth stages) and the surface area went on increasing with the corresponding reduction in soil moisture deficit (Fig. 8). The functional relationship developed between the number of days after showing and root surface area for all treatments at two stages (70 DAS and 100 DAS) have been worked after fitting the most appropriate trend lines and are given below with their respective R^2. Functional relationship between number of days after sowing and the root surface area are given in eqns. 3 and 4:

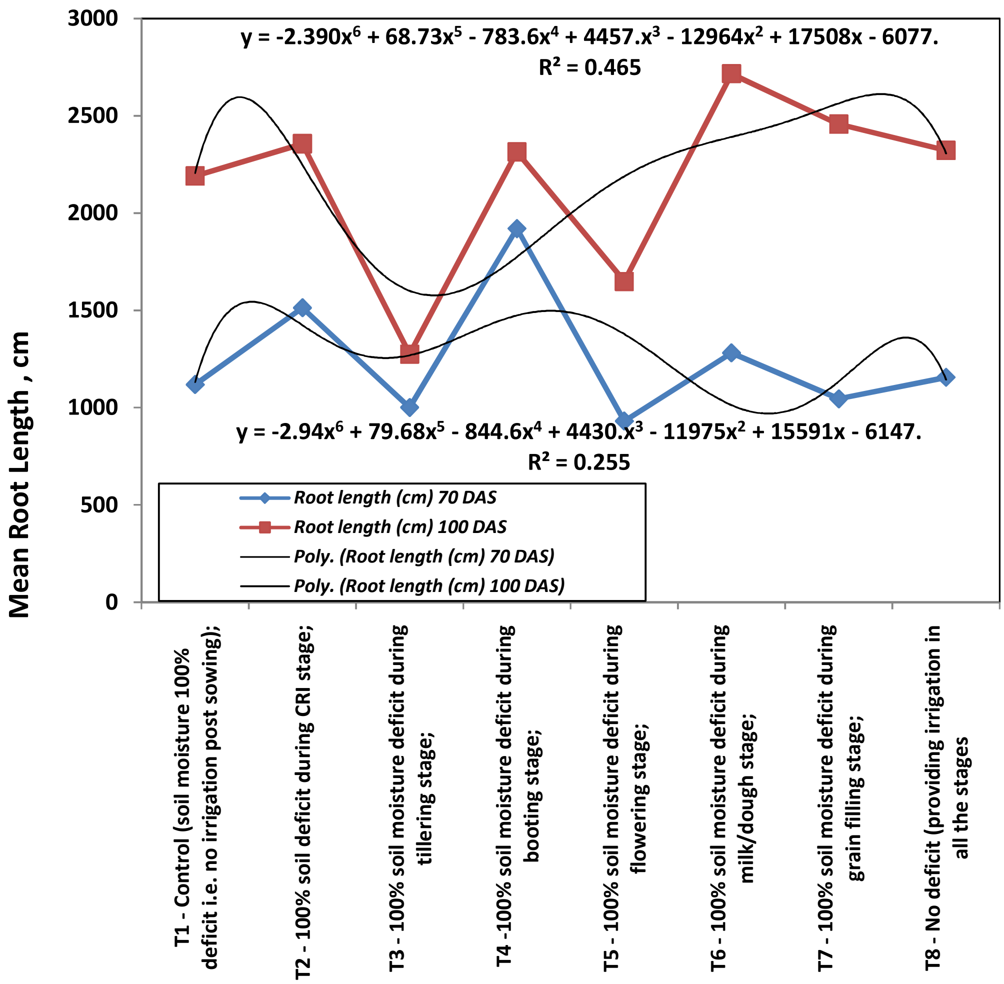


Fig. 5. Effect of soil moisture treatments on mean root length (cm) of wheat (*Triticum aestivum* L.) crop

Table 1. Effect of irrigation treatments on root length (cm) of wheat (*Triticum aestivum* L.) crop under reduced irrigation at Delhi weather conditions

Treatments	70 DAS					100 DAS				
	R1	R2	R3	R4	Mean	R1	R2	R3	R4	Mean
T1	1088.26	1015.22	1245.32	1124.24	1118.26	2166.69	2155.26	2256.35	2184.26	2190.64
T2	1520.47	1458.26	1548.21	1524.21	1512.79	2568.65	2456.32	2154.26	2243.68	2355.73
T3	985.39	1021.25	995.26	1002.30	1001.05	1246.10	1256.35	1325.26	1274.56	1275.57
T4	1938.27	1854.26	1942.50	1945.20	1920.06	2492.00	2153.65	2245.68	2365.26	2314.15
T5	845.55	958.24	1024.21	896.25	931.06	1647.45	1745.26	1548.56	1652.30	1648.39
T6	1273.19	1321.20	1245.26	1284.56	1281.05	2805.95	2463.50	2845.26	2746.56	2715.32
T7	1030.43	1025.23	985.62	1140.30	1045.40	2564.33	2456.36	2449.65	2354.62	2456.24
T8	1188.79	1125.26	1124.20	1184.65	1155.73	2311.45	2263.54	2453.35	2259.23	2321.89
CD at 5% 82.523, C.V-4.5%						*CD at 5% 171.64, C.V- 5.1%*				

T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages

Table 2. Post hoc analysis for root length as affected by reduced irrigation treatments of wheat (*Triticum aestivum* L.) crop at Delhi weather conditions

Treatments	Root length (cm)*			
	70 DAS	% of growth during 70 DAS	100 DAS	% of growth during 70 -100 DAS
T1	1118.26 ^{de}	33.8	2190.64 ^{c}	66.2
T2	1512.79 ^{b}	39.1	2355.73 ^{bc}	60.9
T3	1001.05 ^{fg}	44.0	1275.57 ^{e}	56.0
T4	1920.06 ^{a}	45.3	2314.15 ^{bc}	54.7
T5	931.06 ^{g}	36.1	1648.39 ^{d}	63.9
T6	1281.05 ^{c}	32.1	2715.32 ^{a}	67.9
T7	1045.40 ^{ef}	29.9	2456.24 ^{b}	70.1
T8	1155.73 ^{d}	33.2	2321.89 ^{bc}	66.8

*T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages;*Means with the same letter are not significantly different*

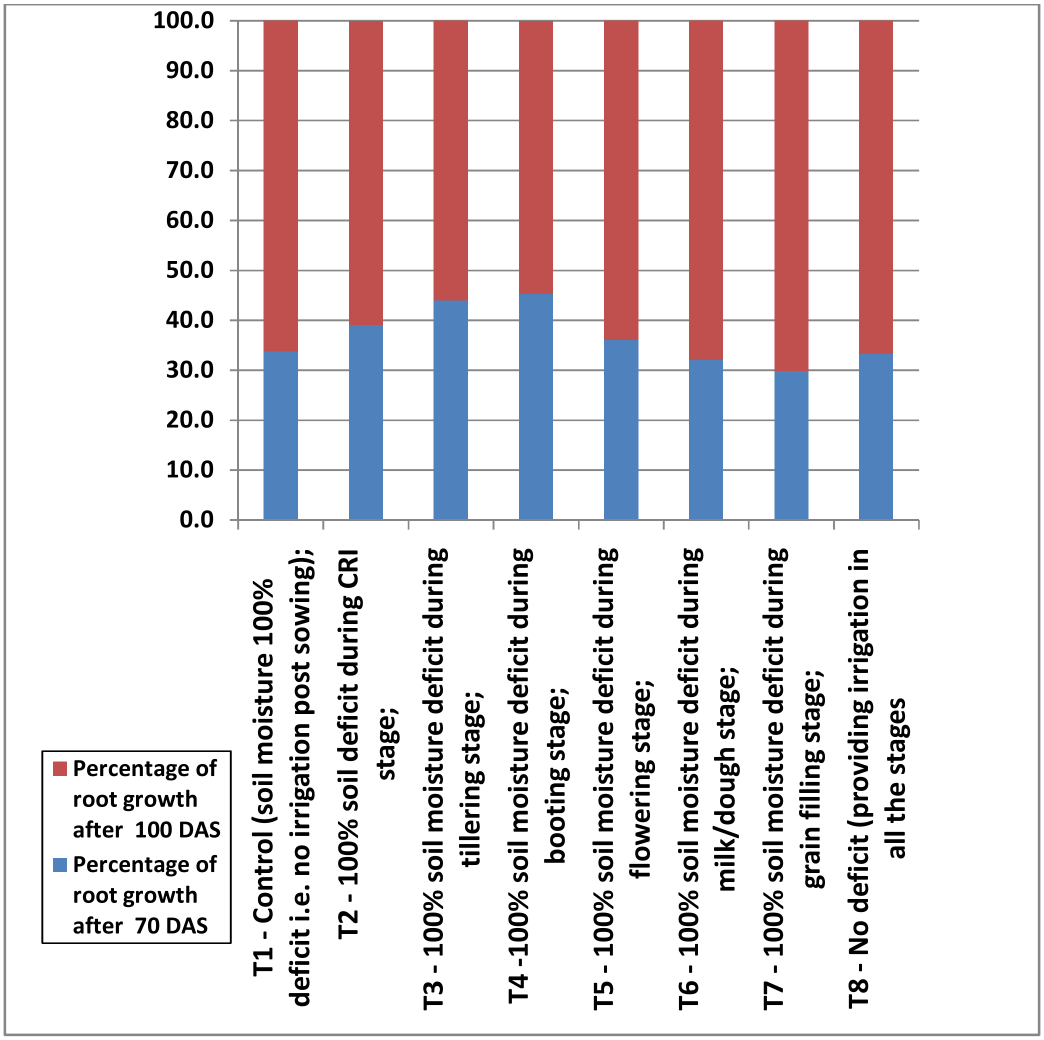


Fig. 6. Relative percentage growth of root length of wheat (*Triticum aestivum* L.) crop after 70 and 100 DAS under different treatment combinations

3.3.1 Functional relationship between number of days after sowing and the root surface area

3.3.1.1 Functional relationship between number of days after sowing and the root surface area 70 das

A fifth order polynomial between Number of Days after Sowing and the Surface Area (70 DAS) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = 0.384x^5 - 5.241x^4 + 12.58x^3 + 70.66x^2 - 283.7x + 512.7 \quad (3)$$

$R^2 = 0.893$

3.3.1.2 Functional Relationship between Number of Days after Sowing and the Root Surface Area 100 DAS

A fourth order polynomial between Number of Days after Sowing and the Surface Area (100 DAS) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = -3.639x^4 + 66.57x^3 - 413.1x^2 + 1005.x - 464.0 \quad ....(4)$$

$R^2 = 0.906$

Based on the R^2 values in both the functional relationships (eq. 3 & 4) it is quite clear that the root surface area showed a well defined trend in the growth patterns after 70 and 100 DAS as expecetd. In this case too, the wheat plant responded in a much balanced manner as regards to plant root surface area increased. This means that although the roots have not elongated much in length they have gained horizontal thickness and became stronger to cope up with the soil moisture stress induced mechanical impedance. The pattern was much more matured and explicit after 70 DAS to 100 DAS (R^2 = 9.06).

3.4 Effect of Irrigation Treatments on Root Surface Volume (X100 Cm^3) of Wheat (*Triticum aestivum* L.) Crop

The treatment and replication wise root volume of wheat (*Triticum aestivum* L.) crop under reduced irrigation after 70 DAS and 100 DAS are presented in Table 5 wherein the mean root volume have also been worked out (Table 5). It was observed that after 70 DAS the minimum root volume of only 365 cm^3 was recorded in T1 (i.e. pre sowing but no irrigation in all growth stages) followed with 426 cm^3 in T2 (i.e. – 100% soil deficit during CRI stage). The maximum root volume (524 cm^3) was observed in treatment T5 (i.e. no irrigation during flowering stage); preceded by T7 (517 cm^3) (i.e. No irrigation during grain filling stage) which is natural. Whereas, in case of 100 DAS, the highest root volume of 816 cm^3 was recorded in the treatment T2 (No irrigation during CRI stage); followed with 672 cm^3 in T2 which is No irrigation during CRI stage. The Post-hoc analysis is presented in Table 6. On persuasion of Tables 5 and 6 it is quite clear that the root volume were significantly affected by the levels of treatments. In case of route volume a definite trend as per the treatment details could be established from the data of root volume of various treatments for 70 DAS as well as 100 DAS (eqn. 5 and 6). However, in this case also it is quite difficult to draw a final conclusion and a clear cult idea about root volume fluctuations did not emerged. However, it could be inferred from the trends that the root volume is not affected in the same intensity as the root length and root surface area (Fig. 9) which was very sensitive and root surface area which showed a relatively lower sensitivity to the moisture sensitive stages. Nevertheless, from this exercise at least it has emerged that root and shoot growth are related and they exhibit almost a similar behavior to the input management with same or similar growth patterns. Majority of the root development seems to have concentrated in the period after 70 DAS (Fig. 10). More precise studies would therefore, be desirable to clearly establish the relationships by doing precise and controlled experiments in Phytotrones, therefore. The functional relationship developed between the number of days after showing and root volume (cm^3) for all treatments at two stages (70 DAS and 100 DAS) have been worked after fitting the most appropriate trend lines and are given below with their respective R^2 (eqn. 5 & 6). Functional relationship between number of days after sowing and the root volume (cm^3) for 70 and 100 DAS are discussed below:

3.4.1 Functional relationship between number of days after sowing and the root volume

3.4.1.1 Functional relationship between number of days after sowing and the root volume (x100) 70 DAS

A sixth order polynomial between Number of Days after Sowing and the Root Volume (X100) (700 DAS) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = -2.94x^6 + 79.68x^5 - 844.6x^4 + 4430.x^3 - 11975x^2 + 15591x - 6147 \quad (5)$$

$R^2 = 0.255$

3.4.1.2 Functional relationship between number of days after sowing and the root volume (x100) 100 DAS

A sixth order polynomial between Number of Days after Sowing and the Root Volume (X100) (100 DAS) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = -2.390x^6 + 68.73x^5 - 783.6x^4 + 4457.x^3 - 12964x^2 + 17508x – 6077 \quad (6)$$

$R^2 = 0.465$

Like the root length in the case of root volume too the R^2 values in both the functional relationships (eq. 5 & 6) are not very encouraging that supports the statement made as above regarding the root growth patterns after 70 and 100 DAS. It can be seen from these values that after 70 DAS till the 100 DAS the plant responded in a much balanced manner as regards to plant root volume than 70 DAS which showed an indefinable/ zig-zag pattern.

Table 3. Effect of irrigation treatments on root surface area (cm^2) of wheat (*Triticum aestivum* L.) crop under reduced irrigation at Delhi weather conditions

Treatments	70 DAS					100 DAS				
	R1	R2	R3	R4	Mean	R1	R2	R3	R4	Mean
T1	292.45	325.26	295.63	311.25	306.15	183.09	193.56	203.65	189.65	192.49
T2	261.76	248.56	248.26	304.25	265.71	373.87	384.65	345.21	356.24	364.99
T3	251.15	325.26	265.63	289.65	282.92	347.86	325.36	365.58	324.26	340.77
T4	450.77	355.26	412.25	384.56	400.71	300.13	285.36	288.59	299.65	293.43
T5	355.01	322.12	322.15	311.25	327.63	225.40	255.64	254.29	245.25	245.14
T6	295.34	256.23	286.36	298.56	284.12	419.08	400.12	374.48	412.25	401.48
T7	153.71	165.23	211.25	168.26	174.61	441.51	402.26	385.99	415.26	411.25
T8	360.11	340.26	302.25	324.56	331.79	332.59	351.26	298.57	320.26	325.67
CD at 5% 40.86 C.V-9.36 %						*CD at 5% 25.97, C.V-5.48%*				

T1 - Control (soil moisture 100% deficit i.e. no irrigation post sowing); T2 - 100% soil deficit during CRI stage; T3 - 100% soil moisture deficit during tillering stage; T4 -100% soil moisture deficit during booting stage; T5 - 100% soil moisture deficit during flowering stage; T6 - 100% soil moisture deficit during milk/dough stage; T7 -100% soil moisture deficit during grain filling stage; T8 - No deficit (providing irrigation in all the stages)

Table 4. Post hoc analysis for root surface area (cm^2) as affected by reduced irrigation treatments of wheat (*Triticum aestivum L.*) crop at Delhi weather conditions

Treatments	Root surface area (cm^2)			
	70 DAS	% of growth during 70 DAS	100 DAS	% of growth during 70 -100 DAS
T1	306.15 ^{bc}	61.4	192.49 ^{f}	38.6
T2	265.71 ^{c}	42.1	364.99 ^{b}	57.9
T3	282.92 ^{c}	45.4	340.77 ^{bc}	54.6
T4	400.71 ^{a}	57.7	293.43 ^{d}	42.3
T5	327.63 ^{b}	57.2	245.14 ^{e}	42.8
T6	284.12 ^{c}	41.4	401.48 ^{a}	58.6
T7	174.61 ^{d}	29.8	411.25 ^{a}	70.2
T8	331.79 ^{b}	50.5	325.67 ^{c}	49.5

**Means with the same letter are not significantly different; T1 - Control (soil moisture 100% deficit i.e. no irrigation post sowing); T2 - 100% soil deficit during CRI stage; T3 - 100% soil moisture deficit during tillering stage; T4 -100% soil moisture deficit during booting stage; T5 - 100% soil moisture deficit during flowering stage; T6 - 100% soil moisture deficit during milk/dough stage; T7 - 100% soil moisture deficit during grain filling stage; T8 - No deficit (providing irrigation in all the stages)*

3.5 Effect of Irrigation Treatments on Root Biomass (X100 g) of Wheat (*Triticum aestivum* L.) Crop

The treatment and replication wise root biomass (x100 g) of wheat (*Triticum aestivum* L.) crop under reduced irrigation after 70 DAS and 100 DAS are presented in Table 7 wherein the mean root biomass have also been worked out and subjected to statistical analysis (Table 8). It was observed that after 70 DAS the minimum root biomass of only 1400 g recorded in T1 (i.e pre sowing but no irrigation in all growth stages) followed with 1950 g in T2 (i.e. – 100% soil deficit during CRI stage). The maximum root biomass (2910 g) was observed in treatment T7 (i.e.– No irrigation during grain filling stage); preceded by T3 (2680 g) (i.e. – No irrigation during Tillering stage;) which is quite unnatural. Whereas, in case of 100 DAS, the highest root biomass of 7350 g was recorded in the treatment T8 which is Full Irrigation in all the crop growth stages followed with 7352 g in T1 (i.e. Pre sowing +No irrigation in all growth stages) (Fig. 11). The functional relationship between root biomass after 70 and 100 DAS have also been worked out from the trendline that was plotted (Fig. 11). The Post-hoc analysis is presented in Table 8. On persuasion of Tables 7 and 8 it is quite clear that the root biomass were significantly affected by the levels of treatments (Fig. 12). In case of route biomass a definite trend as per the treatment details could be established from the data of root biomass of various treatments for 70 DAS as well as 100 DAS (Eqn. 7 and 8). Nevertheless, it is noticeable that the relative percentage of root biomass of wheat (*Triticum aestivum* L.) crop after 70 DAS was significantly lower (nearly 1/3rd) as compared to the root biomass accumulation in next 30 days as recorded after 100 DAS (Fig. 12) under different treatment combinations. However, in this case also it is quite difficult to draw a final conclusion and a clear cult idea about root biomass fluctuations did not emerged. However, it could be inferred from the trends that the root biomass is not affected in the same capacity as the root length which was very sensitive and root surface area and root volume which showed a relatively lower sensitivity to the moisture sensitive stages. Nevertheless, from this exercise at least it has emerged that root and shoot growth are related and they exhibit almost a similar behavior to the input management with same or similar growth patterns. More precise studies would therefore, be desirable to clearly establish the relationships by doing precise and controlled experiments. Functional relationship between number of days after sowing and the root biomass was developed (eqn. 7 & 8).

Table 5. Effect of irrigation treatments on root volume (x100 cm^3) of wheat (*Triticum aestivum* L.) crop under reduced irrigation at Delhi weather conditions

Treatments	70 DAS					100 DAS				
	R1	R2	R3	R4	Mean	R1	R2	R3	R4	Mean
T1	3.21	4.25	4.26	3.65	3.84	8.63	8.56	8.15	8.65	8.50
T2	4.55	5.24	4.26	4.26	4.58	6.59	6.57	6.45	7.26	6.72
T3	5.66	4.26	5.26	5.24	5.11	7.32	7.15	7.26	7.48	7.30
T4	4.26	4.56	4.59	4.59	4.50	8.34	8.54	8.45	8.59	8.48
T5	4.22	4.85	4.59	4.69	4.59	7.86	7.56	7.58	8.05	7.76
T6	5.62	4.56	5.24	5.12	5.14	5.45	6.25	5.86	6.12	5.92
T7	5.58	6.25	5.48	5.17	5.62	8.83	8.21	8.59	8.12	8.44
T8	4.25	5.85	4.26	4.59	4.74	8.68	8.54	8.95	8.45	8.66
	CD at 5% 0.73 C.V- 10.42 %					*CD at 5% 0.39, C.V- 3.47%*				

T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages

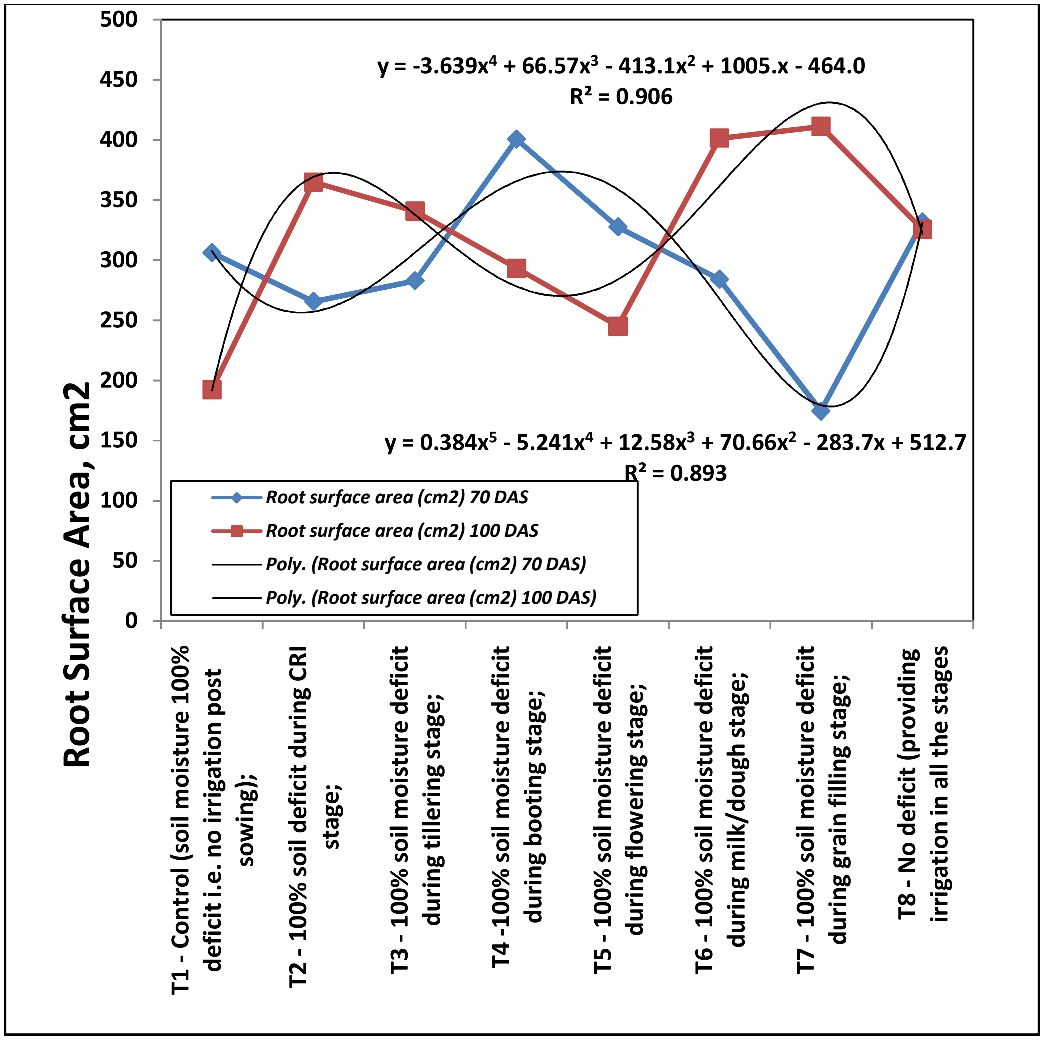


Fig. 7. Effect of soil moisture treatments on mean root surface area (cm2) of wheat (*Triticum aestivum* L.) crop

3.5.1 Functional relationship between number of days after sowing and the root biomass

3.5.1.1 Functional relationship between number of days after sowing and the root biomass (x100 g) 70 DAS

A sixth order polynomial between Number of Days after Sowing and the root biomass (x100 g) (70 DAS) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = 0.041x^6 - 1.173x^5 + 12.87x^4 - 68.90x^3 + 185.1x^2 - 226.7x + 112.7 \quad (7)$$

$R^2 = 0.982$

3.5.1.2 Functional relationship between number of days after sowing and the Root biomass (x100 g) 100 DAS

A sixth order polynomial between Number of Days after Sowing and the Root Biomass (x100 g)) of the type below; was fitted and the value of R^2 was worked out to be:

$$y = -0.207x^6 + 5.308x^5 - 52.17x^4 + 247.2x^3 - 579.8x^2 + 615.7x - 162.6 \quad (8)$$

$R^2 = 0.994$

Based on the R^2 values in both the functional relationships (eq. 7 & 8) it is quite clear that the root biomass which is a combined indicator of all the parameters listed above viz., root length, root surface area and root volume, showed a very well defined trend in the growth patterns after 70 and 100 DAS. This clearly established the impact of soil moisture deficit during initial to developmental to maturity stages that soil moisture has a very strong influence on the total root biomass. In this case, during both periods i.e. 70 DAS as well as 100 DAS the trend of the root biomass accumulation curves could be defined with a very high degree of accuracy (R^2 = 0.982 for 70 DSA and = 0.994 for 100 DAS). Hence, wheat crop responded in a much balanced manner as regards to plant root biomass and the influence of the soil moisture deficit has been pronounced except in the treatments which go slightly disturbed due to intermittent rains (Fig. 13).

3.6 Effect of Reduced Irrigation on Plant Height of Wheat Crop

There was no significant difference in plant heights amongst various treatments in early vegetative stages of wheat crop (40 DAS). However, in the later stages i.e., (70 and 100 DAS) during late vegetative and reproductive phases; various treatments exhibited significant differences in the plant heights as compared to the control (T1). T1, T3 and T6 were amongst the treatments which were not significantly different with respect to plant height during late vegetative stages. Similarly, the treatments T1, T3, T5, T6 and T7 did not exhibit significant differences in plant heights although; all of them had significantly different heights during reproductive stage those were significantly different with the control.

Table 6. Post hoc analysis for root volume (x 100 cm^3) as affected by reduced irrigation treatments of wheat (*Triticum aestivum* L.) crop at Delhi weather conditions

Treatments	Root volume (x 100 cm^3) *			
	70 DAS	**% of growth during 70 DAS**	**100 DAS**	**% of growth during 70 -100 DAS**
T1	3.84 ^{c}	30.0	8.50 ^{a}	70.0
T2	4.58 ^{bc}	38.8	6.72 ^{d}	61.2
T3	5.11 ^{ab}	41.8	7.30 ^{c}	58.2
T4	4.50	35.1	8.48 ^{a}	64.9
T5	4.59 ^{b}	37.7	7.76 ^{b}	62.3
T6	5.14 ^{ab}	46.4	5.92 ^{e}	53.6
T7	5.52 ^{a}	38.0	8.44 ^{a}	62.0
T8	4.74 ^{b}	34.6	8.66 ^{a}	65.4

*T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages; *Means with the same letter are not significantly different*

Table 7. Effect of irrigation treatments on root biomass (x100 g) of wheat (*Triticum aestivum L.*) crop under reduced irrigation at Delhi weather conditions

Treatments	70 DAS					100 DAS				
	R1	**R2**	**R3**	**R4**	**Mean**	**R1**	**R2**	**R3**	**R4**	**Mean**
T1	4.1	13.6	18.1	15.5	14.0	33.1	73.9	69.8	70.5	73.5
T2	5.8	23.8	22.3	18.1	19.5	30.2	43.3	42.4	46.8	48.8
T3	7.2	24.1	22.4	27.6	26.8	37.4	52.3	51.9	54.3	54.6
T4	5.5	19.4	20.9	21.1	20.7	37.5	71.2	72.2	72.6	72.8
T5	5.4	20.5	22.3	21.5	21.5	36.1	59.4	57.3	61.0	62.5
T6	7.2	25.6	23.9	26.8	26.3	28.0	34.1	36.6	35.9	36.2
T7	7.1	34.9	34.3	28.3	29.1	49.6	72.5	70.5	69.8	68.5
T8	5.4	24.9	24.9	19.6	21.8	41.1	74.1	76.4	75.6	73.2
	CD at 5% 0.974 C.V- 10.42 %					*CD at 5% 0.499, C.V- 3.47%*				

T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages

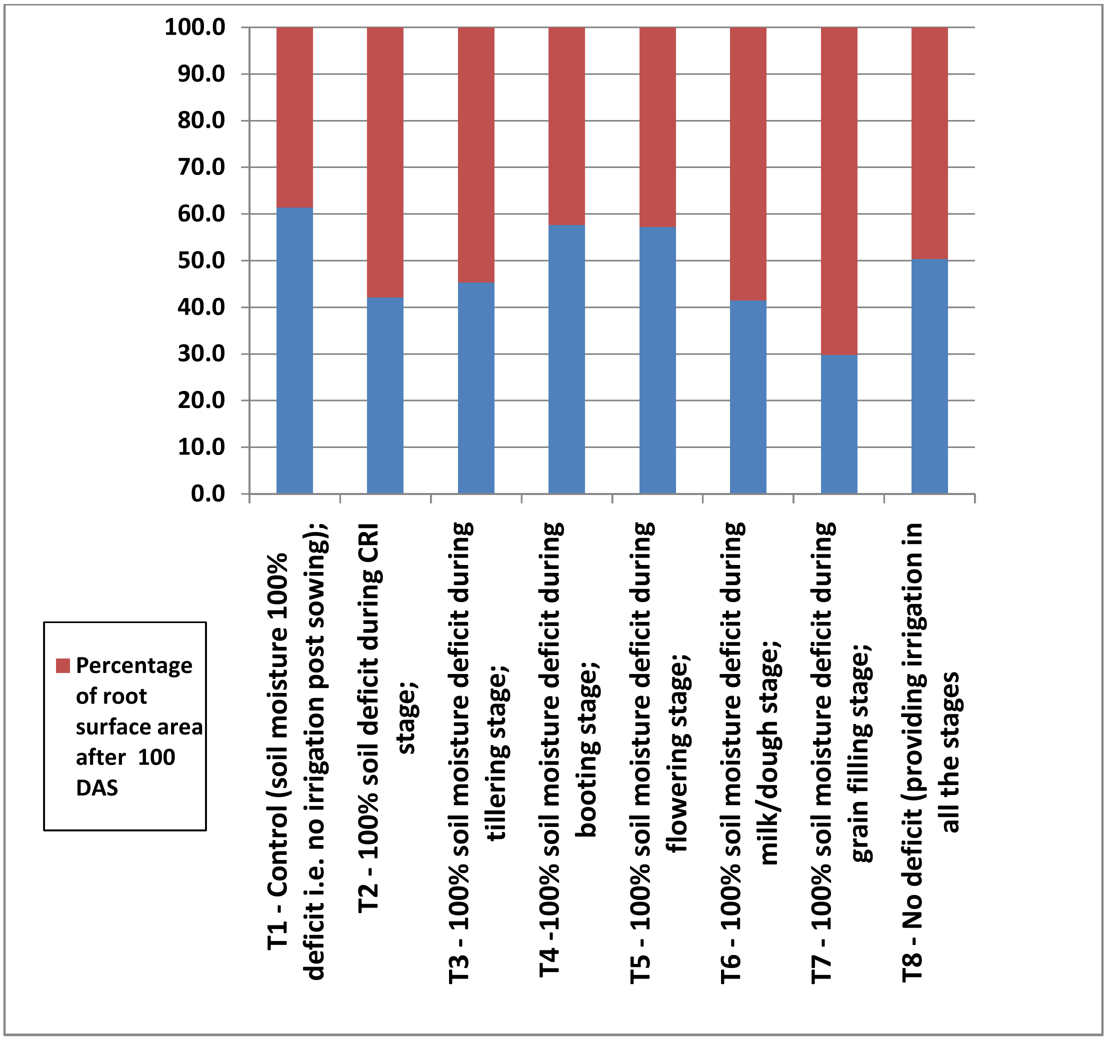


Fig. 8. Relative percentage growth of root surface area of wheat (*Triticum aestivum* L.) crop after 70 and 100 DAS under different treatment combinations

Table 8. Post hoc analysis for root biomass (x 100 g) as affected by reduced irrigation treatments of wheat (*Triticum aestivum* L.) crop at Delhi weather conditions

Treatments	Root biomass (x100 g) *			
	70 DAS	% of growth during 70 DAS	100 DAS	% of growth during 70-100 DAS
T1	14.0^{c}	30.0	73.5^{a}	70.0
T2	19.5^{bc}	38.8	48.8^{d}	61.2
T3	26.8^{ab}	41.8	54.6^{c}	58.2
T4	20.7	35.1	72.8^{a}	64.9
T5	21.5^{b}	37.7	62.5^{b}	62.3
T6	26.3^{ab}	46.4	36.2^{e}	53.6
T7	29.1^{a}	38.0	68.5^{a}	62.0
T8	21.8^{b}	34.6	73.2^{a}	65.4

*T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages *Means with the same letter are not significantly different*

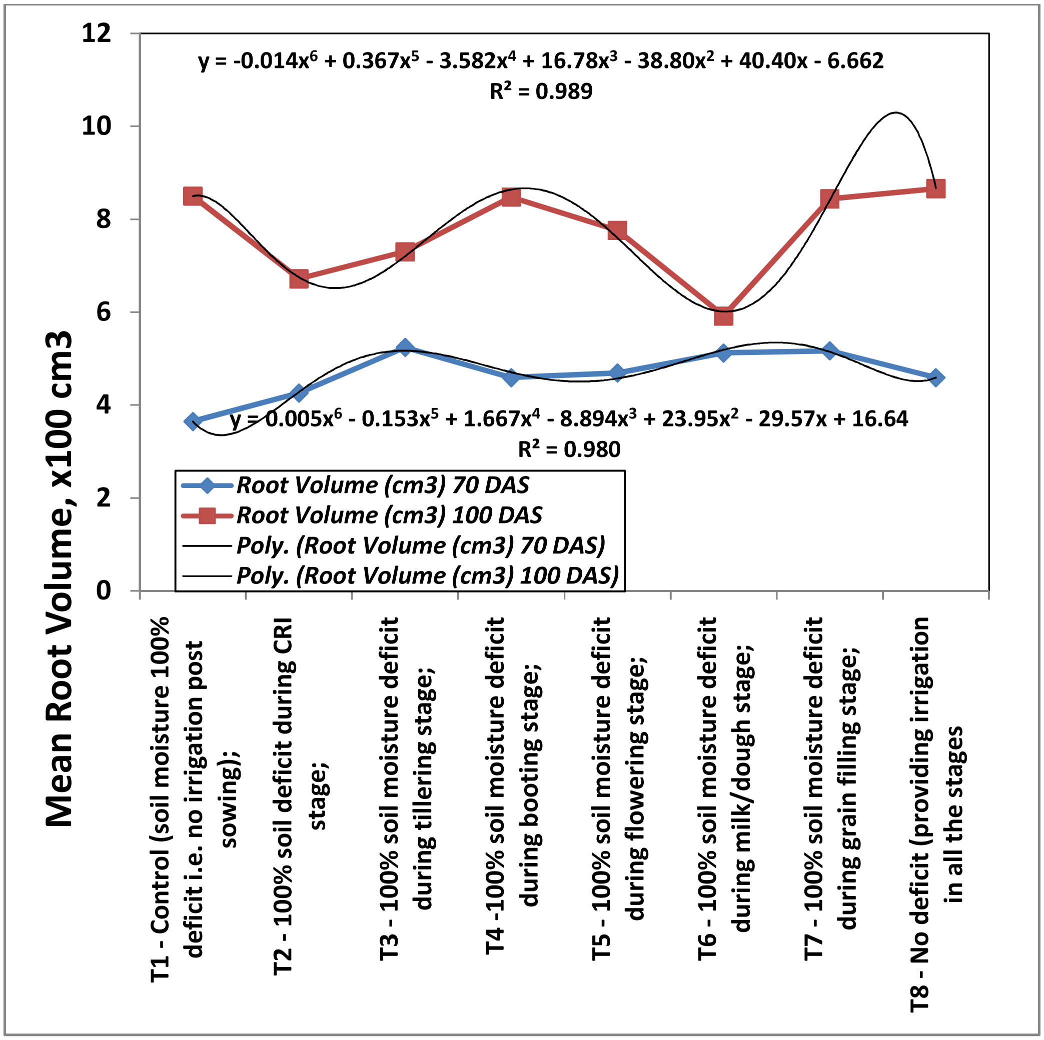


Fig. 9. Effect of soil moisture treatments on mean root volume (x100 cm3) of wheat (*Triticum aestivum* L.) crop

3.7 Effect of Reduced Irrigation on Plant Growth, Development of Number of Tillers

Similarly, significant differences were observed in number of tillers/m2. Persistence of the higher assimilatory surface leaf area is a pre-requisite for prolonged photosynthate activity vis-à-vis higher dry matter accumulation and ultimately crop productivity. Since plant height, number of tillers plays and leaf area plays an important role in photosynthesis [39,40,61], it may be understood that these growth parameters contributes significantly in the development of “source”. Since there are significant differences in source development, it may be interpreted that it will also affect the yield of the crop. Yield results reveal that there is a positive correlation between LAI and grain weight (r = 0.728).

3.8 Effect of Reduced Irrigation on Leaf Area Index (LAI)

An indicator of the overall health conditions of the crop is the Leaf Area Index (LAI) of the plant which eventually is a combined result of soil moisture status, soil fertility and disease free atmosphere. Consequently, the LAI has been consistently high in almost all growth stages in all the treatments but the trend has remained the same. This has been directly related with the soil moisture status and can rightly be attributed to the main contributor. The leaf area index (LAI) in different plant growth stages, were found to be statistically significant differences as a result of reduced irrigation. Similar results were obtained by other workers too [9,39]. As our main emphasis here is the root architecture hence, this factor (Leaf Area Index (LAI)) is not being subjected to elaborate discussions.

3.9 Dry Matter Production

Leaf Area Index (LAI) is closely related with the dry matter production [11]. Dry matter accumulation was estimated in three main crop stages i.e., tillering, flowering and milking stages respectively. In order to estimate the dry matter partitioning it was accounted for root, stem, leaves and spikelets separately. It is worth noticing that skipping irrigation in CRI and milking stages had significant decrease in the dry matter accumulation [40,30] even though the treatment with no water deficiency (T8) recorded highest dry matter accumulation. To calculate the amount of irrigation water, differences among treatment in allocating the sources from the sink were observed.

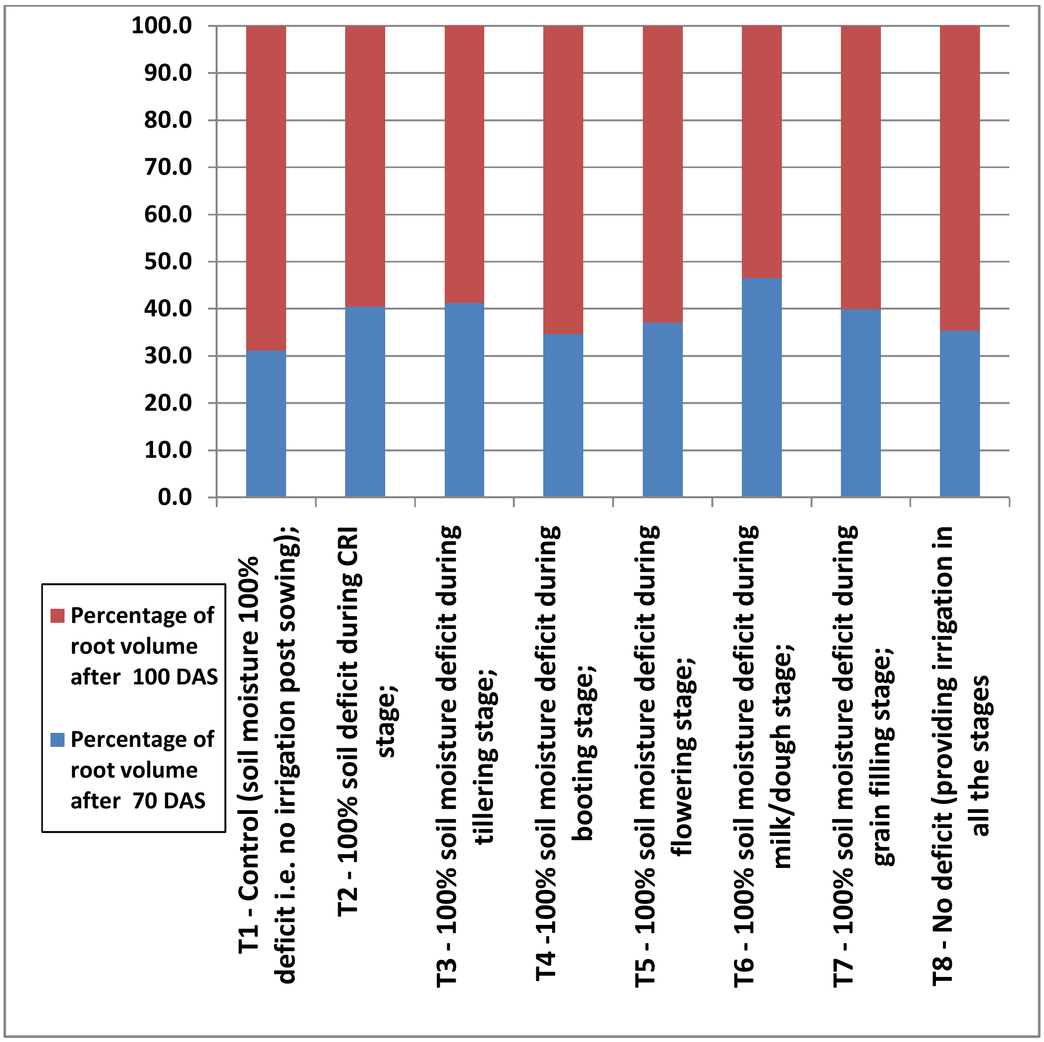


Fig. 10. Relative percentage growth of root volume of wheat (*Triticum aestivum* L.) crop after 70 and 100 DAS under different treatment combinations

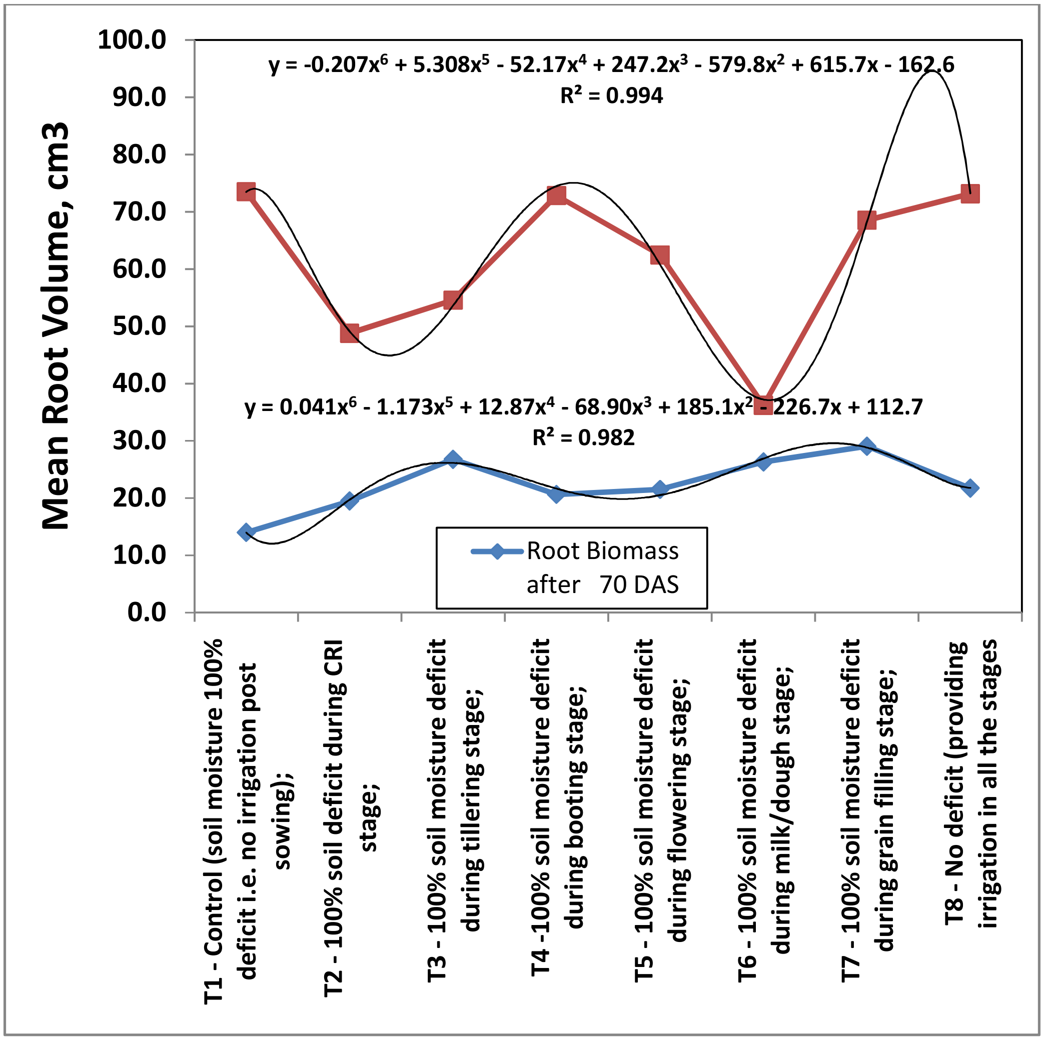


Fig. 11. Effect of soil moisture treatments on mean root biomass (x100 g) of wheat (*Triticum aestivum* L.) crop after 70 and 100 DAS

3.10 Soil Moisture Dynamics

Soil moisture content was estimated. The soil moisture changes during the crop period were also recorded by book keeping method. After the pre-sowing irrigation which coincides with the onset of winters in Northern India, the temperature becomes low to extremely low the evapotranspiration losses are limited to minimum. Hence, the second and third stages of crop keep on surviving on the root zone soil moisture. Estimating the soil moisture content before irrigation can be an important criteria to schedule irrigation and also irrigating with the required moisture content [29,62]. The effective rainfall due to rainfall as estimated using standard procedures which has been duly accounted in the irrigation scheduling procedures (Fig. 13).

3.11 Yield and Yield Attributes

Although, there was no significant difference in the grain weight among T3, T4 and T8 the treatment with no irrigation (T1) has shown drastic reduction in grain weight (Table 9). It is also observed that treatment T2 has adversely affected the grain weight. The results are presented in Fig. 14. The relationship between grain weight and LAI is also illustrated through regression analysis (Fig. 14). Due incessant rainfall in the field in the preceding week of harvesting that resulted into inability in threshing of the produce having higher moisture contends,

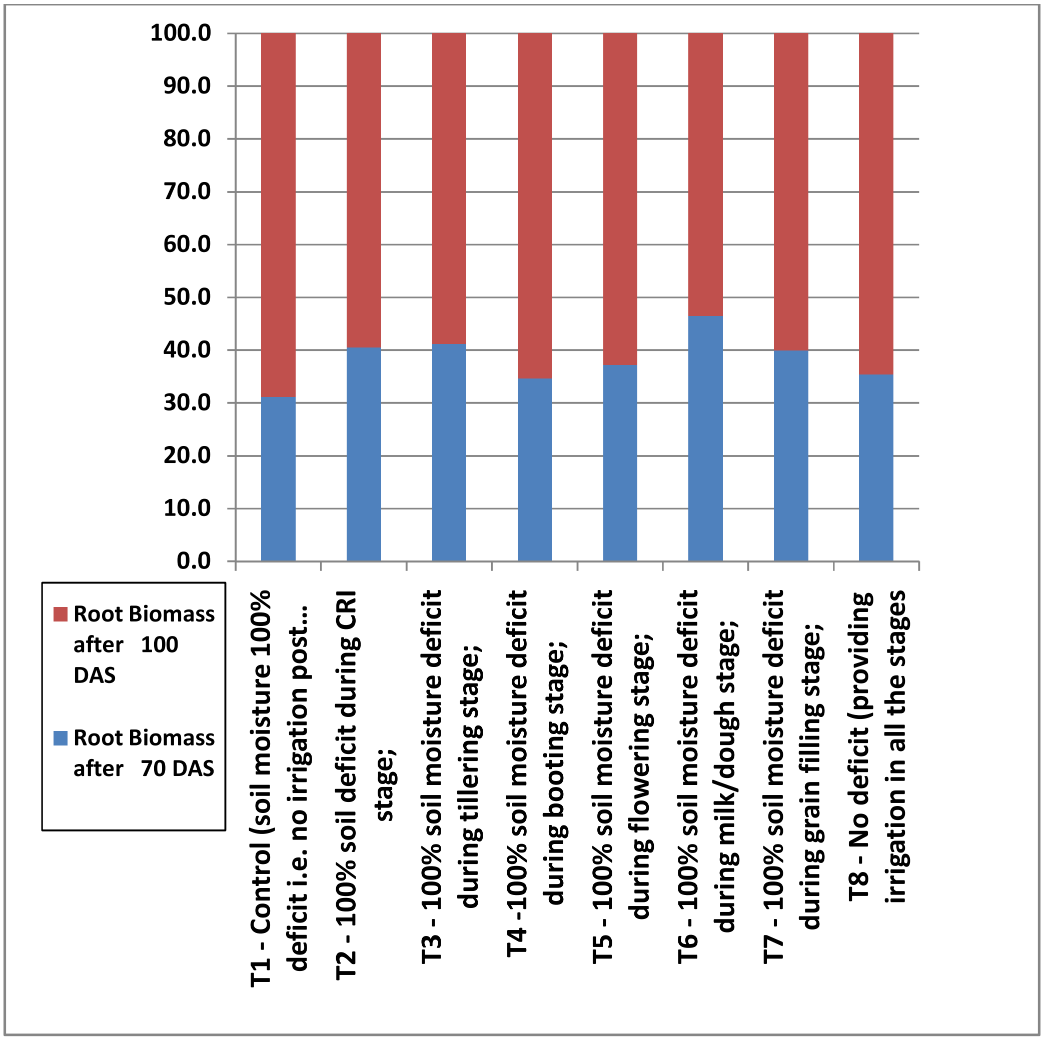


Fig. 12. Relative percentage of root biomass of wheat (*Triticum aestivum* L.) crop after 70 and 100 DAS under different treatment combinations

the results of grain yields could not be reported. An equation between LAI and plant dry matter accumulation has been developed based on the research results.

Grain weight (y) = 0.682. Leaf Area Index (x) + 0.8083 (9)

$R^2 = 0.538$

A general variation of the major climatic parameters at the study area (Fig. 13) indicated that though the maximum and minimum temperatures have behaved quite normally, the rainfall at the station was quite consistent. There were several rainstorms (seven) of the order of 5mm to more than 20 mm which has affected the crop yield quite favourably by adding moisture to the soil during this year. During the third week of November (sowing period) to second week of February the minimum temperature reduced drastically which in turn had resulted into a substantial reduction in the evaporative demand of the atmosphere. This might have been the major reason for non-significant changes in the crop parameters in the initial two crop growth stages followed with a very heavy pre-sowing irrigation which has resulted into non-significant variation among the first two stages. In the later parts of the crop growing season however, the significant changes in different crop growth parameters have been observed and recorded due to improved climatic conditions. This is a clear cut reason for keeping the crop without water for so long by some farmers after sowing it with pre-sowing irrigation of more than 50 mm or fully saturating the soil profile

3.12 Effect of Soil Moisture Stress on Root Morphometry, Architecture and Physiology

Plant roots are strongly affected by soil water potential and physical characteristics. A plant responds to a lack of water by halting growth and reducing photosynthesis and other plant processes in order to reduce water use [63-67]. As water loss progresses, leaves of some species may appear to change color—usually to blue-green. Foliage begins to wilt and, if the plant is not irrigated, leaves will fall off and the plant will eventually die. Similar changes have been found to be occurring in the plat root system as well [68-71]. Soil Moisture stress lowers the water potential of a plant's root and upon extended exposure, abscisic acid is accumulated and eventually stomata closure occurs [72-75]. This reduces a plant's leaf relative water content. The time required for drought stress to occur depends on the water-holding capacity of the soil, environmental conditions, stage of plant growth, and plant species. Plants growing in sandy soils with low water-holding capacity are more susceptible to drought stress than plants growing in clay soils. A limited root system will accelerate the rate at

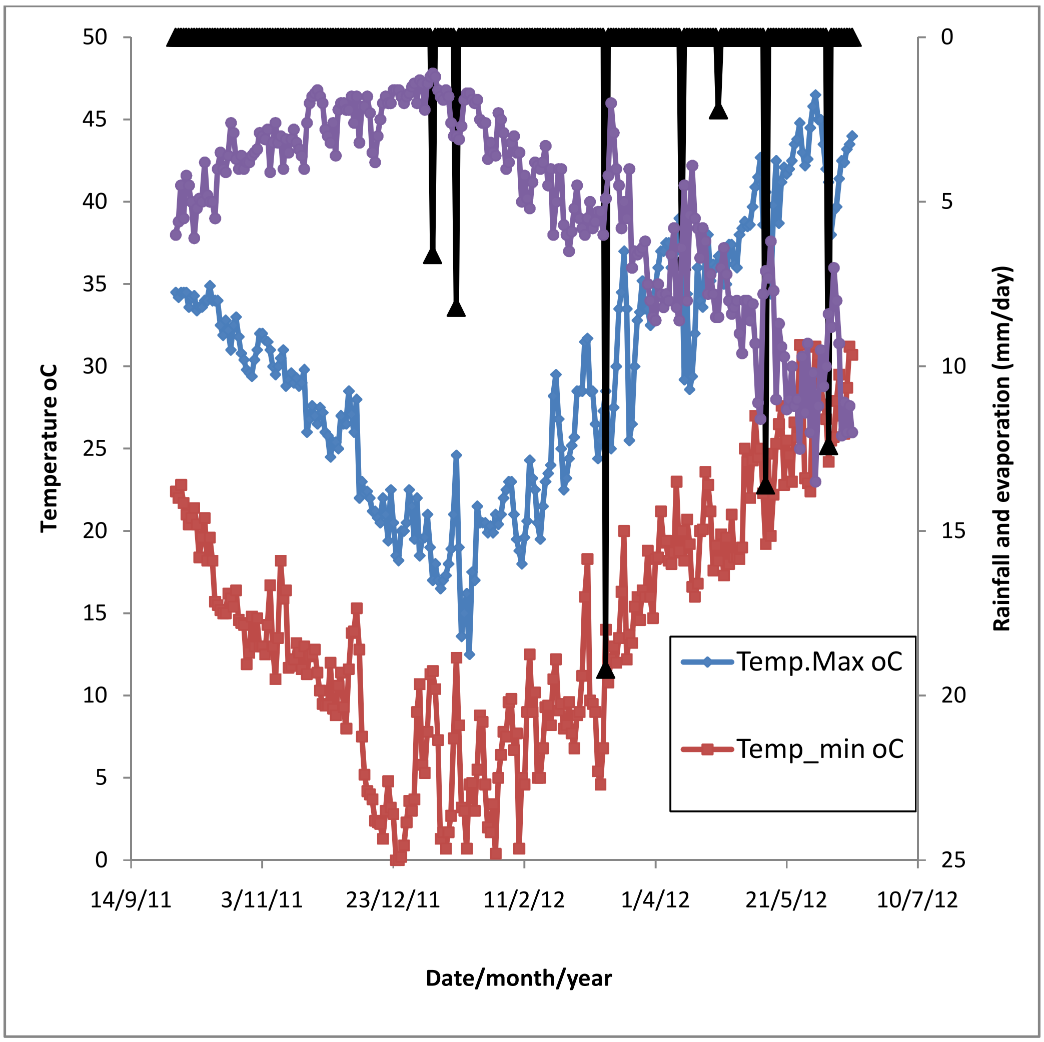


Fig. 13. General variations in the major climatic parameters during the wheat (*Triticum aestivum* L.) crop growing season (rabi) of the year 2011-12 at IARI Pusa observatory, New Delhi, India

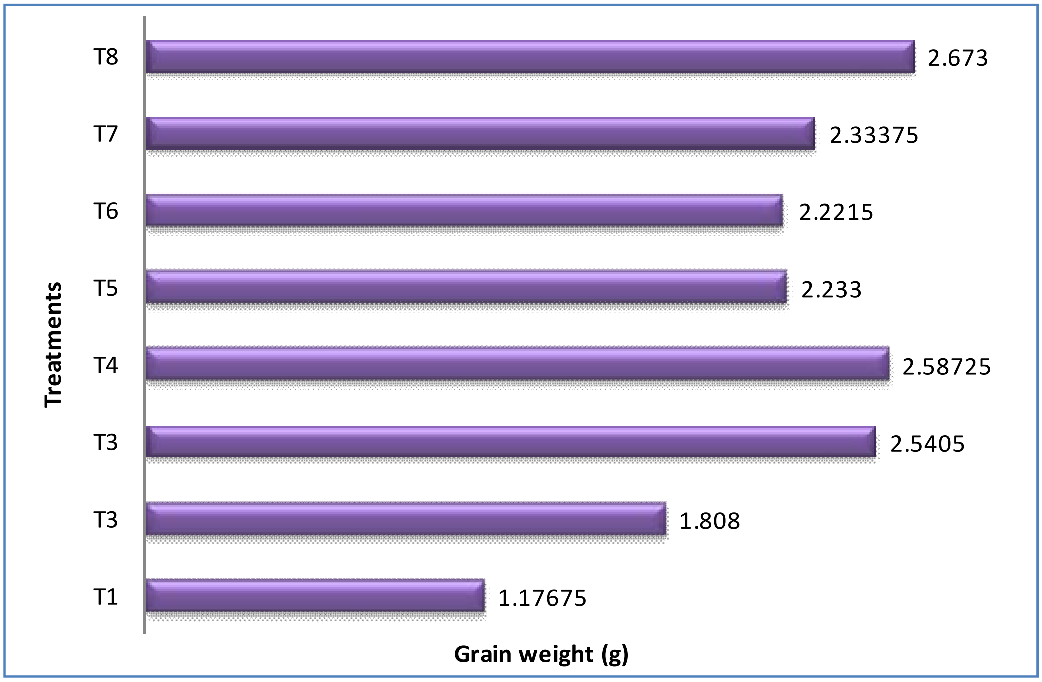


Fig. 14. Grain weight (gram/spikelet) in wheat (*Triticum aestivum)* crop under reduced irrigation at different stages of crop growth (Var. Pusa Hybrid HD-2967)

T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages

which drought stress develops. A root system may be limited by the presence of competing root systems, by site conditions such as compacted soils or high water tables, or by container size (if growing in a container). A plant with a large mass of leaves in relation to the root system is prone to drought stress because the leaves may lose water faster than the roots can supply it. Newly installed plants and poorly established plants may be especially susceptible to drought stress because of the limited root system or the large mass of stems and leaves in comparison to roots [76,77]. Soil mechanical impedance against root growth and development is caused mainly by natural processes and by the use of heavy machinery for soil cultivation [78,79]. The root system of an individual plant consists of several component roots of different nature. Those components differ in external morphology, physio-logical function and genetic control. According to [80], root system structure of cereal plant consists of seminal, seminal adventitious, nodal and lateral roots. The seminal and nodal roots build up the framework, while lateral roots of different orders build network of the roots in soil. The cereal species develop two types of root system, depending on the angle of growth of branches (lateral roots) and their distribution in a soil profile [81]. Highlighting on water relation of plants in soil stresses, many studies indicate that leaf water status is influenced through several mechanisms [82,83]. According to [84] root borne signals affect the rate of development in the apical meristem, cell division and cell expansion in the expanding leaves and they induce stomata behavior. Root signals are expected to be electrical and hormonal (ethylene, ABA, auxin and likely cytokinin signaling cascades) and are involved in mediating physiological effects. Understanding of processes in which the photosynthesis and gas exchange rate are depressed by soil compaction requires more physiological studies on roots and shoots. Since development of a whole root system consisting of root components was closely related to productivity of wheat; the crop yield also was affected due to soil moisture stress in different growth stages (Tables 2, 9). However, there are huge genetic variations among the cultivars with regard to shoot and root characteristics [85,86] as well as ambient climatic and edaphic characteristics of the place of experiment [87,88].

Table 9. Grain weight and above ground biomass as affected by different irrigation treatments (different stages) of wheat (*Triticum aestivum* L.) crop under reduced irrigation at Delhi weather conditions

Treatments	Yield parameters	
	Grain weight/ spikelet (g)	Above ground biomass (t/ha)
T1	1.18	8.58
T2	1.81	13.76
T3	2.54	19.79
T4	2.59	19.19
T5	2.23	18.07
T6	2.22	15.79
T7	2.33	22.56
T8	2.67	21.14
S.E.(d)	*0.134*	*1.764*
C.D. (5 %)	*0.29*	*3.692*

T1 - Control (Pre sowing +No irrigation in all growth stages), T2 – No irrigation during CRI stage; T3 – No irrigation during Tillering stage; T4 –No irrigation during Booting stage; T5 – No irrigation during Flowering stage; T6 – No irrigation Milk/Dough stage; T7 –No irrigation during grain filling stage; T8 – Full Irrigation in all the crop growth stages

4. CONCLUSION

In this experiment; the water requirement in the initial stages of crop growth and development was low as compared to other stages due to extreme low temperature, high humidity, and low sunshine hours and near zero wind that brought down the evaporative demand of the atmosphere. However, during the later part of the year, the evaporative demand has eventually increased resulting into higher atmospheric/ evaporative demand and thus the effect of reduced irrigation was pronounced. Control treatment T1 (with no irrigation) recorded a significant difference with T8 treatment (no water deficiency) in all traits studies (the root morphology, leaf area index, soil moisture dynamics and crop yields), that were closely associated but these traits showed significant differences among the treatments. It was established that under different critical crop growth stages plants response to the stress conditions varied differently to fulfill their metabolic activities. However, the successive critical growth stages were not completely different to each other based on statistical significance tests.

Results of the present study confirmed that root volumes as well as biomass were significantly affected due to skipping irrigation in crop sensitive stages eg. CRI, flowering and grain filling crop growth stages. Root growth and development are important parameter in managing the crop in reduced irrigation conditions. The results have clearly demonstrated that that each root related parameter varies with each treatment (Tables 2, 4, 6, 8). Root dynamics study is important to understand the nutrient and water uptake since it is directly related with yield. Functional relationships developed in this study may be used for understanding the root growth and development under soil moisture stress conditions in various crop growth stages. The study needs to be conducted under rain shelter or phytotrones for better control of the parameters.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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