Chapter 1

Effect of Phosphorus on Root Signaling of Wheat under Different Water Regimes

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Additional information is available at the end of the chapter

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Abstract

Phosphorus (P) is one of the most vital nutrient needed for crop production. Phosphorus plays an important role in root growth and builds resistance against abiotic stresses. In the current study two wheat cultivars (phosphorus responsive) were planted to study the treatment effects in polythene bags. The treatments were 5 different levels of P (P_0 = 0.2 g/bag, P_{60} = 0.4 g/bag, P_{80} = 0.53 g/bag, P_{100} = 0.66 g/bag and P_{120} = 0.8 g/bag) and three water regimes. The data regarding root length, shoot length, root-shoot ratio and yield parameters were collected and analyzed. Among both the genotypes, NARC-2009 performed well compared to Sehar-06. The highest dry matter and yield were obtained under P_{100} compared to other treatments. With the increased phosphorus root and shoot length increased linearly up-to P_{100} while afterward it starts decreasing. The results lead to conclusion that optimum dose of phosphorus could be used to increase root growth and establishment under water stress.

Keywords: phosphorus, abiotic stresses, dry matter, root growth and root establishment

1. Introduction

Root signaling is the response of the plant roots on different stimuli like soil structure, soil nutrients, different chemicals and stress conditions. Root apical meristems are the major sites for different types of activities in response to changes related to roots. Root growth defines the extent to which plant explores soil for water and mineral nutrients. Root systems of individual crop plants may encounter large variations in mechanical impedance to root penetration [1]. Root architecture is a highly plastic and environmentally responsive trait that enables

plants to counteract nutrient scarcities with different forging strategies [2]. Root-specific traits such as root system architecture, sensing of edaphic stress and root-to-shoot communication can be exploited to improve resource capture (water and nutrients) and plant development under water-limited conditions [3].

The uptake of nutrients depends upon both the supply of available nutrients in the rooting media and the root system [4]. The ability of plants to respond appropriately to nutrient availability is of fundamental importance for their adaptation to the environment. Nutrients such as nitrate, phosphate, sulfate and iron act as signals that can be perceived. These signals trigger molecular mechanisms that modify cell division and cell differentiation processes within the root and have a profound impact on root system architecture. Important developmental processes, such as root-hair formation, primary root growth and lateral root formation, are particularly sensitive to changes in the internal and external concentration of nutrients [5]. There is no doubt that differences occur in response to mineral nutrition both among species and cultivars, that is, genotypes belonging to the same species.

Phosphorus plays a vital role in crop production and is involved in energy transfer in plants. Carbon dioxide fixation by plants is not possible without phosphorus. Many plant physiological functions such as utilization of sugars, starch, photosynthesis, energy storage and transfer are dependent on phosphorus. It is also a constituent of cell nucleus and is essential for cell division and development of meristematic tissues [6]. Phosphorus has been reported to increase the strength of cereal straw, resist abiotic stresses, stimulate root development, promote flowering, fruit production, and formation of seed and hasten maturity of the crops [7]. Phosphorus utilization efficiency can be improved by mixing it with farm yard manure to increase the yield of wheat. Farm yard manure mixed with single superphosphate in 1:2 ratio increases phosphorus efficiency significantly [8]. It would be advantageous if we select, screen or improve plants for higher capacity to adapt to mineral stresses. This approach is beneficial in developing countries like Pakistan where capital input resources are limited. Farmers in these countries require nutrient efficient crop cultivars which perform better or do something better than other cultivars when given a considerable amount of mineral nutrient.

Cereals are facing acute problem of drought and temperature stress [9]. Low water availability is the major environmental factor which limits crop productivity. Root is the place where plants first encounter drought stress, it is likely that roots may be able to sense and respond to stress condition. Drought stress is the most common adverse environmental condition that can seriously reduce crop productivity [10, 11]. The mechanism of drought tolerance and breeding for drought-resistant crop plants has been major goal of plant biologists and crop breeders. Significant progress has been made in understanding root growth under drought stress. However, there has been no genetically defined drought-adaptive response in root development. But inhibition of lateral root development is a typical adaptive response of roots to drought stress. Despite the lack of understanding of drought tolerance mechanisms, physiological and molecular biological studies have documented several plant responses to drought stress [12].

Lack of sufficient water is the most important factor affecting world agriculture. Thus, increasing the efficiency of water and nutrient use is essential in order to improve yield whilst minimizing damage to the environment [13–18]. Plant depends upon the capacity of roots to obtain water and nutrients from the soil. The root respiration, carbohydrates allocation (root: shoot

ratio) and grain yield are closely related to soil water status. Reductions in root respiration and root biomass under severe soil drying can improve drought tolerant wheat growth and physiological activity during soil drying and improve grain yield, and hence should be advantageous over a drought sensitive cultivar in arid regions. Therefore objectives of the study were (i) to examine the effect of phosphorus on root signaling of wheat and (ii) to determine the effect of water stress on root signaling. The hypothesis, therefore made, was that there is a significant relationship present between wheat roots and P and also between root and drought stress.

2. Root signaling

2.1. Phosphorus and root signaling

Among all essential plant nutrients, phosphorus (P) is the second most abundantly required nutrient element after nitrogen and is an important constituent of many structural components of the plants [19, 20]. In agricultural ecosystems, it determines the soil quality with respect to its production capacity [21]. Being scarce and non-renewable natural resource [22] which is under the threat of rapid depletion as a result of intensive mining across the world more emphasis is being given to increase P use efficiency in soil for successful and sustainable crop production. A field experiment was conducted over 2 years to study the ameliorating effects of P on wheat yield, root cation exchange capacity (CEC) and on different doses of P. Phosphorus was applied as single superphosphate. The application of P increased the root CEC of wheat up to bloom stage only whereas nutrient concentration, uptake and grain and straw yield were found to increase up to maturity [23]. The capacity of plant roots to increase their carboxylate exudation at low plant phosphorus (P) status is an adaptation to acquire sufficient P at low soil P availability. Root mass ratio decreased with increasing P supply for *Triticum aestivum* L. [24]. An experiment was set up to make a critical assessment of the role of organic P in soil solution in the nutrition of wheat plants under sterile conditions. Phosphorus supply had a positive effect on dry matter and P concentration of the plants. Acid phosphatase secretion by plant roots was 5–11 times higher in organic P treatments than in the inorganic P treatments. It was hypothesized that plants secrete phosphatases in response to the presence of organic P in soil solution and organic P might be responsible for the increase in P influx to wheat plants [25].

Root-soil contact is an important factor for uptake of a less mobile soil nutrient such as phosphorus (P) by crop plants. Root hairs can substantially increase root-soil contact. Identification of crop cultivars with more and longer root hairs can, therefore, be useful for increasing P uptake in low input agriculture. The variation in root hair parameters of the cultivars was related to quantity of P depleted from rhizosphere. These results showed that the variation in root hairs of cereal cultivars can be considerable and it can play a significant role in P acquisition, especially in low-P soils [26]. A field trial was conducted to investigate main morphological and physiological changes of different wheat landraces to low-P stress at the stage of seedling. P-deficiency significantly decreased root volume, total leaf area, and plant dry weight, but greatly increased density of root hairs and root top ratio. In addition, P-deficiency induced the significant enhancement of phosphorus utilization efficiency and the amount of

proline, malondialdehyde, acid phosphatase, peroxidase and superoxide dismutase (SOD), but the significant reduction of P uptake and soluble protein content. The results based on the correlation analysis showed that the economic yield of wheat landraces had relationships with their morphological and physiological characteristics under P-deficiency [27].

2.2. Drought and root signaling

Effect of drought on the growth and yield of wheat were investigated. Drought during grain filling further decreased yields. Plots with a lower plant density demonstrated a smaller decrease in yield due to drought. There was a significant positive linear relationship between the number of shoots per plant and nodal root axes per plant. There appeared to be a difference between cultivars in root system architecture, and in their response to drought, but these differences were not reflected in grain yield [28]. Drought-induced loss in crop yield probably exceeds losses from all other causes, since both the severity and duration of the stress are critical. Drought stress reduces leaf size, stem extension and root proliferation, disturbs plant water relations and reduces water-use efficiency. Plants display a variety of physiological and biochemical responses at cellular and whole-organism levels towards prevailing drought stress, thus making it a complex phenomenon. Plants display a range of mechanisms to withstand drought stress. The major mechanisms include curtailed water loss by increased diffusive resistance, enhanced water uptake with prolific and deep root systems and its efficient use, and smaller and succulent leaves to reduce the transpirational loss. At molecular levels several drought-responsive genes and transcription factors have been identified, such as the dehydration-responsive element-binding gene, aquaporin, late embryogenesis abundant proteins and dehydrins. Plant growth substances such as salicylic acid, auxins, gibberellins, cytokinin and abscisic acid modulate the plant responses towards drought. Polyamines, citrulline and several enzymes act as antioxidants and reduce the adverse effects of water deficit [29]. The possibility of reducing the proliferation of roots to increase yields at higher seeding rates and conserving the soil water at different growing stages in water-limited environments was studied. In the severe drought towards the end of the growing season, grain yield decreased as the seeding rate increased, but under the more favorable conditions the reverse was true. Averaged over the seeding rates, grain yield was significantly increased; grain yield and yield components were higher and root pruning at spring-growth stage recorded the highest water use efficiency [30]. The leaf net photosynthetic rate and stomatal conductance were significantly decreased under drought. The leaf transpiration rate was decreased by drought. The intercellular CO_2 concentration was increased under drought, while it was decreased most of the time from midday to the afternoon. The leaf stomatal limitation was increased under drought [31].

Root length, root dry weight and seedling dry weight are the major traits to select for studying tolerant genotypes under water stress conditions [32]. It is reported that drought affect the plant water status during ear formation and flowering stage. Water availability mostly affects growth of leaves, roots, photosynthesis and dry mater accumulation [33].

2.3. Phosphorus × drought and root signaling

Phosphorous availability is correlated with moisture conditions of the soil, because higher water content in soil due to frequent irrigation generally leads to a better mobility and

availability of P [34], which also improves the P conversion in the internal of plant [35], by enhancing root-shoot ratio and root elongation releasing of organic acids or protons [36] and phosphatases [37]. The absorbed P by plant to produce more biomass is another adaptive mechanism to P deficiency in soil, thus low-P also limits the yield and quality of wheat [38], because P can effect on photosynthesis, photo-assimilate transportation and stunt growth of plant [39–41]. Further, the coupling effect of water and chemical fertilizers on different crops or varieties have been reported by many studies, they revealed that water and nutrient uptake were two physiological processes that interacted with each other [42–45]. Therefore, soil water content and P fertilizer, and meanwhile, their interaction plays great key role for crop growth [46], and suitable irrigation and fertilization is the main method to increase production. The effects of drought stress on the phosphorus (P), uptake dynamics throughout the growth cycle were studied. Drought stress induced sharp decreases in total P uptake at different developmental stages and, in particular, detrimentally affected the nutrient uptake capability of roots. The results suggested that plants differ in their ability to maintain nutrient uptake under drought stress, and it is highly dependent on the intensity and duration of drought stress and the developmental stage. The decrease in total P uptake caused by both moderate stress and severe stress was accompanied by reduction in biomass production in drought-stressed tissues. The biomass allocation patterns in response to drought stress fluctuated strong mostly because of competitive changes in the shoot and roots at different stages, thus the root: shoot ratio increased at some stages and decreased at other stages. Severe stress induced a dramatic reduction in the harvest index, whereas moderate stress slightly decreased harvest index. Thus, water limitation caused lower P uptake and harvest index [47].

The water content and nutrient in soil are two main determinant factors to crop yield and quality, managements of which in field are of great importance to maintain sustainable high yield. The objective of the study was to measure the uptake, forms, and use efficiency of phosphorus in wheat under irrigation. The results indicated that P fertilizer combined with irrigation not only improved the activity of phosphatase in soil, but also increased P accumulation in wheat, similar results was found in the grain of wheat, the content of total P increased significantly. The interaction between P and irrigation also significantly affected on the P accumulation, grain total P, grain phospholipids P, and P production efficiency [48].

3. Materials and method

Two experiments were carried out to study root signaling in response to different water regimes and level of phosphorus. First one was about screening of wheat genotypes for drought tolerance conducted in the laboratory. The sowing apparatus used was Petri dishes (9 cm diameter) in which 9 different varieties of wheat were sown under different level of PEG (polyethylene glycol) to induce stress. From these 9 varieties two varieties which gave better results under drought conditions were selected. These two varieties were further sown in the second experiment which was conducted in a polythene bags (2.5 feet long, 10 cm diameter). In the second experiment eight treatments were applied which were replicated thrice. The detail of both the experiments is given as under.

3.1. Experiment # 1

Lab experiment was conducted at PMAS-Arid Agriculture University Rawalpindi. Nine wheat varieties were selected namely, Sehar-06, Wafaq-2001, Freed-06, Dhurabi, NARC-09, NARC-11, Lasani-08, Bars-09 and Punjab-11. Thirty seeds were randomly selected from each variety and were sterilized with ethanol solution. PEG6000 solution was prepared at three different concentrations viz; 12.5 g/250 ml (−0.50 bars) ($PEG_{-0.50}$), 25 g/250 ml (−1.48 bars) ($PEG_{-1.48}$) and 37.5 g/250 ml (−2.95 bars) ($PEG_{-2.95}$). The sterilized seeds of the above mentioned nine varieties were placed in the Petri dishes on the filter papers soaked with the above mentioned solutions of PEG. The sowing was done on 23rd October 2013. The effect of PEG on germination and seedling vigor traits of wheat varieties were studied to check which variety performed well under higher concentrations of PEG producing higher degree of drought.

3.1.1. Germination and seedling vigor traits (10–20 days)

Germination percentage was taken 10 days after sowing. Total number of seeds sown and the number of seeds germinated were counted and germination percentage was calculated. Fresh roots (of one plant per petri dish) were taken and were individually weighed on a weighing balance to get root fresh weight. After taking the fresh weight, the roots were oven dried for 24 h at 65°C. After 24 h they were weighed on a weighing balance for measurement of root dry weight. Length of individual roots was measured with the help of a foot ruler. The roots of the plants were removed and the above root portion, that is, shoot were weight on a weighing balance for the measurement of shoot fresh weight. After taking fresh weight, the shoots were oven dried for 24 h at 65°C and after that they were weighed on a weighing balance for shoot dry weight. Root and shoot lengths were separately measured with the help of a foot ruler and then the ratio was taken.

3.2. Experiment # 2

From experiment # 1 two varieties (NARC-09 and Sahar-06) were selected which performed well under higher PEG concentrations showing their adaptation under drought conditions. These two varieties were then sown for further study. Equal quantity of sand (72 kg) and soil (72 kg) were mixed and filled in polythene bags. Phosphorus was applied to the soil prior to sowing. Ten seeds of selected genotypes were sown in each bag. Measured amount of water was added in treatments involving drought study while in phosphorus treatments water was applied before sowing. The experimental area was covered with polythene sheet to hinder the supply of water to the water treatments due to rain. The treatments includes; T1 = at field capacity (control), T2 = 10% below field capacity, T3 = 20% below field capacity, T4 = 0.2 g/bag (30 kg/ha), T5 = 0.4 g/bag (@ 60 kg/ha), T6 = 0.53 g/bag (@ 80 kg/ha), T7 = 0.66 g/bag (@ 100 kg/ha) and T8 = 0.8 g/bag (@ 120 kg/ha). Phosphorus was applied in the form of P_2O_5. Number of replications were three, therefore, the total number of treatments were 48. The experimental design used was completely randomized (CRD).

3.2.1. Crop parameters and statistical analysis

Root length was taken at three leaf, anthesis and maturity with the help of a foot ruler. Roots of the plant were separated from the shoot and also any soil, if present, was removed. Afterwards the samples were weighed on a weighing balance. Root-shoot ratio was calculated by first measuring the root length and then the shoot length and then the ratio was calculated. Root fresh weight was measured by weighing the root samples on a weighing balance. Fresh root samples were oven dried for 24 h and weighed afterwards on a weighing balance. Root fresh weight and root dry weight are separately measured and then the ratio was calculated. Number of spikelets per spike was calculated of three spikes and then average was taken. Numbers of seeds of three spikes were counted and then its average was taken to get number of seeds per spike. Spikes were collected from the plants and were weighed on a weighing balance to get spike weight. 100 grains were separated on the seed counting tray and weight of those 100 grains were calculated on a weighing balance. The data obtained was statistically analyzed. Analysis of variance (ANOVA) were used to determine means and LSD at 5% level of significance was determined to compare means.

4. Result and discussion

4.1. Experiment # 1 (screening analysis)

Experiment 1 was conducted for screening analysis to select best wheat genotypes. Highest germination percentage was recorded for T2 (87.78%) followed by T1 (87.03) while lowest was at T4 (80.1%) (**Table 1**). There was 20% difference among T2 and T4. In the meanwhile, all the genotypes behaved differently for germination percentage. Maximum germination (96.67%) was recorded for genotype NARC-2009 while minimum germination percentage (76.50%) was recorded for genotype Dhurabi. There was 8% difference among genotype NARC-2009 and Dhurabi for germination percentage. The interactive effects were statistically significant at 1% P level. Maximum germination percentage was recorded for NARC-2009 (100%) at T1 and T2 while minimum germination percentage was recorded for genotype BARS-09 (66.67%) under T1. The treatments depicted significant effect on root fresh weight of different genotypes. All the genotypes varied considerably for root fresh weight (RFW) (**Table 2**). Maximum root fresh weight was recorded for genotype NARC-2009 (0.12 g) while minimum root fresh weight was recorded for genotype Lasani-08 (0.09 g). There was 24% difference among NARC-2009 and Lasani-08 for root fresh weight. Similarly, all the treatments differed potentially for root fresh weight. Maximum root fresh weight was recorded for T1 (0.11 g) while minimum root fresh weight was observed under T3 (0.08 g). In the same way the interactive effects for root fresh weight was potentially significant at 1% P level. Maximum root fresh weight was recoded for genotype NARC-2009 under T1 (0.14 g) followed by genotype Sehar-06 under T2 while minimum root fresh weight (0.06 g) was recorded for genotype Lasani-08 under T4. Results depicted significant variation for root length for different treatments on wheat

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	73.33e–g	76.67d–g	86.67a–e	73.33e–g	77.5CD
Fareed-06	80c–g	86.67a–e	83.33b–f	86.67a–e	84.17BC
NARC-11	96.67ab	93.33a–c	90a–d	73.33e–g	88.33B
Sehar-06	90a–d	80c–g	93.33a–c	93.33a–c	89.17B
Punjab-11	90a–d	93.33a–c	86.67a–e	80c–g	87.5B
Wafaq-2001	96.67ab	93.33a–c	83.33b–f	80c–g	88.33B
NARC-2009	100a	100a	93.33a–c	93.33a–c	96.67A
BARS-09	66.67g	76.67d–g	86.67a–e	76.67d–g	76.67D
Lasani-08	90a–d	90a–d	66.67g	70fg	79.17CD
Mean	87.04A	87.78A	85.56A	80.74B	
LSD for G	6.7819				
LSD for T	4.5213				
LSD for G × T	13.564				

Table 1. Germination percentage for nine wheat genotypes under four treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

genotypes at three leaf stage. All the treatments differed significantly for root length at three leaf stage (Z-13) for wheat crop (**Table 3**). Maximum root length recorded for T2 (10.9 cm)

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	0.08i–n	0.10g–l	0.010e–k	0.10d–j	0.09BC
Fareed-06	0.12b–d	0.09h–m	0.08k–o	0.10b–h	0.09B
NARC-11	0.10b–h	0.10c–i	0.07l–p	0.07m–p	0.08BC
Sehar-06	0.12a–c	0.11b–d	0.10b–g	0.12ab	0.11A
Punjab-11	0.12b–d	0.09g–m	0.07n–p	0.07m–p	0.09C
Wafaq-2001	0.11b–e	0.10d–j	0.07n–p	0.06op	0.08C
NARC-2009	0.14a	0.14a	0.09f–l	0.12ab	0.12A
BARS-09	0.10b–h	0.10b–h	0.08j–m	0.09f–l	0.09B
Lasani-08	0.11b–f	0.10b–h	0.07l–p	0.06p	0.09C
Mean	0.11A	0.10B	0.08D	0.09C	
LSD for G	0.00904		0.242374		
LSD for T	0.006027		0.250676		
LSD for G × T	0.0181		0.569639		

Table 2. Root length for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	6.56p–r	14.20ab	8.73l–p	6.52qr	9.00EF
Fareed-06	10.97e–k	10.53f–l	11.27d–j	12.07b–i	11.21C
NARC-11	7.07n–q	8.83k–o	9.23j–n	12.5a–f	9.43DE
Sehar-06	14.54a	10.41f–l	13.29a–d	11.25d–j	12.38B
Punjab-11	12.55a–g	12.42a–i	10.39g–l	6.70o–r	10.52CD
Wafaq-2001	11.67d–i	8.95k–n	8.73l–p	7.93m–q	9.32EF
NARC-2009	12.83a–e	14.24ab	14.54a	14.04a–c	13.92A
BARS-09	9.2j–n	7.45n–q	9.9i–m	10.35h–l	9.23EF
Lasani-08	10.23h–l	11.94c–i	6.42qr	4.51r	8.28F
Mean	10.62A	10.99A	10.28AB		9.55B
LSD for G	1.0972				
LSD for T	0.7315				
LSD for G × T	2.1944				

Table 3. Root fresh weight for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

whereas, minimum root length recorded for T4 (9.6 cm) at three leaf stage. Meanwhile, wheat genotypes differed significantly for root length. Genotype NARC-2009 obtained maximum root length (13.9 cm) at three leaf stage however, genotype Lasani-08 obtained minimum root length (8.3 cm). The interactive effect G x T was highly significant at 1% P level. Maximum root length was recorded for Sehar-06 under T1 (14.5 cm) followed by NARC-2009 under T4 (14.0 cm) whereas, minimum root length was recorded for Lasani-08 under T4 (4.5 cm).

Results illustrated significant difference for shoot length for different treatments on wheat genotypes at three leaf stage. All the treatments differed potentially for shoot length (**Table 4**). Maximum shoot length was recorded for T1 (10.8 cm) while minimum shoot length was recorded for T3 (7.9 cm). In the same way all the wheat genotypes varied considerably for shoot length. Highest shoot length was observed for NARC-2009 (11.7 cm) followed by Sehar-06 (11.1 cm) whereas, lowest shoot length was observed for genotype Lasani-08 (8.4 cm). There was 29% difference among genotypes for shoot length. In the meanwhile, the interactive effect was highly significant for shoot length. Highest shoot length was recorded under T1 for NARC-2009 (13.0 cm) while lowest shoot length was recorded under T4 for Lasani-08 (5.6 cm). There was 56% difference among genotypes under different treatments.

All the treatments varied considerably for shoot fresh weight (**Table 5**). Maximum shoot fresh weight was recorded for T1 (0.21 g) while minimum weight was recorded for T4 (0.15 g). There was 27% difference among different treatments. Highest shoot fresh weight was gained by genotype NARC-2009 (0.23 g) while lowest shoot fresh weight gained by genotype Dhurabi (0.15 g). There was 35% difference among genotypes for shoot fresh weight. The interactive effect was significantly different under all the treatments. Highest shoot fresh weight was

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	8.2j–o	8.7h–m	9.13f–l	9.63e–k	8.92BCD
Fareed-06	11.07b–e	8.53i–n	7.57l–p	9.9c–j	9.27BC
NARC-11	9.9c–j	9.8d–j	7.33m–q	6.9n–q	8.48CD
Sehar-06	11.44a–d	11b–e	10.30b–g	11.59a–c	11.08A
Punjab-11	11.04b–e	8.62h–n	6.65o–q	6.90n–q	8.30D
Wafaq-2001	10.83b–f	9.56e–k	6.62o–q	6.02pq	8.26D
NARC-2009	13.04a	13.039a	8.92g–m	11.64ab	11.66A
BARS-09	11.23b–e	10.03b–i	8.02k–o	9.03g–m	9.58B
Lasani-08	10.53b–g	9.93b–i	7.32m–q	5.62q	8.35D
Mean	10.81A	9.91B	7.98D	8.58C	
LSD for G	0.8636				
LSD for T	0.5757				
LSD for G × T	1.7272				

Table 4. Shoot length for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

accumulated for genotype NARC-2009 under T1 and T2 (0.26 g) while minimum was accumulated for Lasani-08 under T4 (0.11 g).

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	0.16i–m	0.17g–l	0.15k–o	0.12no	0.15D
Fareed-06	0.19b–i	0.17g–l	0.15k–n	0.12no	0.15D
NARC-11	0.17h–m	0.19c–j	0.15k–o	0.14l–o	0.16D
Sehar-06	0.23a–c	0.22b–d	0.20b–g	0.19b–h	0.21B
Punjab-11	0.22b–d	0.17g–l	0.13m–o	0.14l–o	0.16D
Wafaq-2001	0.21b–e	0.19d–j	0.13m–o	0.12no	0.16D
NARC-2009	0.26a	0.26a	0.18f–k	0.23ab	0.23A
BARS-09	0.12b–h	0.19b–h	0.16j–m	0.18e–k	0.18C
Lasani-08	0.21b–f	0.19b–h	0.15k–o	0.11o	0.17D
Mean	0.21A	0.20A	0.15B	0.15B	
LSD for G	0.0179				
LSD for T	0.012				
LSD for G × T	0.0359				

Table 5. Shoot fresh weight for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	0.06h–l	0.07d–j	0.06j–m	0.04lm	0.06C
Fareed-06	0.09d–i	0.07e–j	0.07h–l	0.04lm	0.07C
NARC-11	0.07g–k	0.08c–g	0.06j–m	0.05k–m	0.07C
Sehar-06	0.10ab	0.09bc	0.09b–d	0.09b–e	0.09A
Punjab-11	0.09b–f	0.07e–j	0.06k–m	0.06l–m	0.07BC
Wafaq-2001	0.08c–f	0.08c–h	0.06k–m	0.05lm	0.07BC
NARC-2009	0.12a	0.12a	0.08d–h	0.10ab	0.10A
BARS-09	0.08d–h	0.09c–f	0.07g–k	0.07f–k	0.08B
Lasani-08	0.08c–g	0.09c–f	0.06i–m	0.04m	0.07BC
Mean	0.09A	0.08A	0.07B	0.06B	
LSD for G	0.008949				
LSD for T	0.005966				
LSD for G × T	0.0179				

Table 6. Shoot dry weight for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

The treatments varied statistically for shoot dry weight (**Table 6**). Highest shoot dry weight was observed under T1 (0.05 g) while minimum shoot dry weight recorded for T3 (0.04 g). In the same way, genotypes varied potentially for shoot dry weight. The highest shoot dry weight was recorded for genotype NARC-2009 (0.06 g) while, lowest shoot dry weight was recorded for genotype Lasani-08 (0.04 g). There was 23% difference among genotypes for shoot dry weight. In the meanwhile, the interactive effects differed considerably for shoot dry weight under all the treatments. Maximum shoot dry weight was accumulated by NARC-2009 under T1 (0.06 g) whereas, minimum shoot dry weight was accumulated by Lasani-08 under T4 (0.02 g).

The results depicted that there was great difference among treatments and genotypes for root dry weight (**Table 7**). Maximum root dry weight was accumulated for T4 (0.05 g) while minimum root dry weight was recorded for T3 (0.04 g). Similarly, all the genotypes varied potentially for root dry weight. Highest root dry weight was accumulated by genotype NARC-2009 (0.06 g) fallowed by Sehar-06 (0.52 g) while lowest by Lasani-08 (0.04 g). In the same way, the interactive effect for T × G was highly significant. Maximum root dry weight was obtained by NARC-2009 under T4 (0.06 g) while minimum root dry weight was obtained by Lasani-08 under T4 (0.23 g). Maximum root to shoot ratio for fresh weight calculated for T1 (1.08) while minimum was calculated for T3 (0.81) (**Table 8**). In the same way all the genotypes differed significantly for root to shoot ratio. Highest root to shoot ratio was calculated for Dhurabi (1.10) whereas, lowest was calculated for Punjab-11 (0.81). Meanwhile, the interactive effects were highly significant at 1% P level. Highest root to shoot ratio was calculated for NARC-11 under T1 (1.57) while lowest for Wafaq-2001 under T4 (0.76). On the basis of screening results two genotypes were selected for experiment II. Genotypes NARC-2009 and Sehar-06 performed better under treatment 4 so these two genotypes were selected.

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	0.04e–o	0.04f–k	0.04f–k	0.04f–k	0.04B
Fareed-06	0.05c–g	0.04f–m	0.03i–p	0.04f–k	0.04B
NARC-11	0.04f–j	0.04e–h	0.032k–p	0.03n–p	0.04B
Sehar-06	0.06a–d	0.05b–e	0.05e,f	0.06a–c	0.05A
Punjab-11	0.05c–g	0.04f–l	0.03l–p	0.03m–p	0.04B
Wafaq-2001	0.05d–g	0.04e–i	0.03m–p	0.03op	0.04B
NARC-2009	0.06a	0.06ab	0.04e–i	0.06a–c	0.06A
BARS-09	0.04e–i	0.05e–g	0.04h–n	0.04g–n	0.04B
Lasani-08	0.04e–h	0.05e–h	0.03j–p	0.02p	0.04B
Mean	0.05A	0.05A	0.04B	0.04B	
LSD for G	0.00488				
LSD for T	0.003254				
LSD for G × T	0.009761				

Table 7. Root dry weight for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

4.2. Polythene bags results

4.2.1. Shoot length

NARC-2009 exhibited maximum shoot length (6.28) at three leaf stage than Sehar-06 (5.28) (**Table 9**). All the treatments showed significant difference for shoot length at three leaf stage. Highest shoot length was recorded for T7 (8.1 cm) followed by T6 and T8 while lowest shoot length shoot length was recorded for T1 (3.47). In the same way, the interactive effect was also found significant. Maximum shoot length was recorded for NARC-2009 under T7 (8.8 cm) followed by NARC-2009 under T8 (8.54 cm) and Sehar-06 under T7 (8.40 cm) whereas, minimum shoot length was recorded for Sehar-06 under T1 (3.1 cm). NARC-2009 exhibited higher shoot length (63.75 cm) than Sehar-06 (54.37 cm). Meanwhile, all the treatments exhibited significant difference for shoot length at anthesis stage (**Table 9**). Highest shoot length was recorded for T7 (69.00 cm) followed by T8 (64.45), T5 (59.88 cm) and T6 (59.11 cm) while lowest shoot length was recorded by T1 (47.61 cm). In the same way, the interactive effects were varied potentially. Highest shoot length was recorded for NARC-2009 (71.64 cm) under T7 while lowest shoot length was recorded for Sehar-06 under T1 (42.88 cm). Maximum shoot length calculated for NARC-2009 (63.75 cm) while minimum shoot length was calculated for Sehar-06 (54.37 cm) (**Table 9**). In the meanwhile, all the treatments differed significantly for shoot length at maturity stage. Highest shoot length was calculated for T7 (75.21 cm) followed by T8, T5, T4 and T6 while, lowest was calculated for T1 (51.89 cm). Meanwhile, the interactive effects were highly significant at 1% P level. Highest shoot length was calculated for NARC-2009 under T7 (78.08 cm) while lowest for Sehar-06 under T1 (46.74). Crop growth and development is

Genotypes	Control	$PEG_{-0.50}$	$PEG_{-1.48}$	$PEG_{-2.95}$	Mean
Dhurabi	1.26b–d	0.62mn	1.05d–h	1.49ab	1.10A
Fareed-06	1.01d–j	0.84g–m	0.67k–n	0.83g–m	0.84C
NARC-11	1.57a	1.13c–f	0.83g–m	0.55n	1.02AB
Sehar-06	0.79i–n	1.08d–g	0.78i–n	1.03d–i	0.92BC
Punjab-11	0.88f–l	0.69k–n	0.64l–n	1.03d–i	0.81C
Wafaq-2001	0.93e–k	1.07d–h	0.76j–n	0.76j–n	0.88C
NARC-2009	1.02d–j	0.92e–k	0.62l–n	0.83g–m	0.85C
BARS-09	1.22cd	1.35a–c	0.81h–m	0.88g–m	1.06A
Lasani-08	1.03d–i	0.83g–m	1.14c–e	1.24b–d	1.06A
Mean	1.08A	0.95B	0.81C	0.96B	
LSD for G	0.1294				
LSD for T	0.0863				
LSD for G × T	0.2588				

Table 8. Shoot to root ratio for 9 wheat genotypes under 4 treatments (T1 = control, T2 = $PEG_{-0.50}$, T3 = ($PEG_{-1.48}$) and T4 = ($PEG_{-2.95}$)).

primarily dependent upon biotic and abiotic environment prevailing in the vicinity of plants. Roots are the main source of nutrients supply to the plant nutrients to the plant. Our results were in line with earlier work who was of the point of view that phosphorus has been reported to increase the strength of cereal straw, stimulate root development, promote flowering, fruit production, and formation of seed and hasten maturity of the crops [13]. Due to increased availability of P leaf area, green pigments also increased and hence the shoot length increased finally. Our results were supported by Zhang et al. [49] who reported that deficiency of P reduced photosynthetic efficiency in wheat due to reduction in leaf area expansion.

4.2.2. Root length

Both the genotypes varied considerably for root length (**Table 10**) at three leaf stage. Maximum root length was calculated for NARC-2009 (4.3 cm) whereas, minimum root length (3.6 cm) calculated for Sehar-06. There was 14% difference among both the genotypes. Similarly, there was a major difference among all the treatments. Maximum root length (4.6 cm) calculated for treatment T7, minimum root length (3.2 cm) calculated for treatment T1 followed by T2. There was 31% difference among maximum and minimum treatments for root length. The interactions were significant at 1% P level for root length. Highest root length was recorded for NARC-2009 under T7 (4.8 cm) while lowest root length recorded for Sehar-06 (2.9 cm). Wheat genotypes varied considerably for root length at anthesis stage (**Table 10**). Genotype NARC-2009 accumulated highest root length (43.0 cm) whereas, genotype Sehar-06 accumulated lowest root length (35.3 cm). The percentage difference among both genotypes for number of seeds per spike was 18%. In the meanwhile, all the treatments varied noticeably for

Treatments	Three leaf		Mean	Anthesis		Mean	Maturity		Mean
	G1	G2		G1	G2		G1	G2	
T1	3.17d	3.7733d	3.4717D	42.883d	52.337cd	47.61C	46.742d	57.046cd	51.894C
T2	4.2267cd	5.03cd	4.6283CD	53.093b–d	55.72a–d	54.407BC	57.87b–d	60.734a–d	59.302BC
T3	5.2833b–d	6.2867bc	5.785BC	53.093b–d	59.7a–c	56.397BC	57.87b–d	65.072a–c	61.471BC
T4	4.2267cd	5.03cd	4.6283CD	53.093b–d	66.663a–c	59.878AB	57.87b–d	72.664a–c	65.267AB
T5	5.2833b–d	6.2867bc	5.785BC	54.627b–d	68.653ab	61.64AB	59.54b–d	74.833ab	67.186AB
T6	6.34bc	7.5433ab	6.9517AB	51.563cd	66.663a–c	59.113AB	56.201cd	72.664a–c	64.432AB
T7	7.3967ab	8.8a	8.0983A	66.367a–c	71.64a	69.003A	72.338a–c	78.086a	75.212A
T8	6.34bc	7.5433ab	6.9417AB	60.24a–c	68.653ab	64.447AB	65.661a–c	74.833ab	70.247AB
Mean	5.2833B	6.2867A		54.37B	63.754A		59.262B	69.492A	
LSD for G	0.8206			5.6734			6.1844		
LSD For T	1.6412			11.347			12.369		
LSD for G × T	2.3211			16.047			17.492		

Table 9. Shoot length for both genotypes at three leaf, anthesis and maturity.

Treatments	Three leaf		Mean	Anthesis		Mean	Maturity		Mean
	G1	G2		G1	G2		G1	G2	
T1	2.5d	3.49cd	3.17C	35.1b	35.1b	35.1B	34.2b	34.2b	34.2B
T2	3.54b–d	3.71a–d	3.63BC	38.2b	39.3b	38.8B	37.2b	38.2b	37.7B
T3	3.54b–d	3.97a–c	3.75BC	40.3b	63.0a	51.7A	39.2b	61.3a	50.2A
T4	3.54b–d	4.44a–c	3.99AB	31b	32.0b	31.5B	30.1b	31.1b	30.6B
T5	3.64b–d	4.57ab	4.11AB	29.9b	25.8b	27.9B	29.1b	25.1b	27.1B
T6	3.44cd	4.44a–c	3.94AB	37.2b	41.3b	39.3B	36.2b	40.2b	38.2B
T7	4.42a–c	4.77a	4.60A	40.3b	69.2a	54.8A	39.2b	67.3a	53.2A
T8	4.02a–c	4.57ab	4.29AB	29.9b	38.2b	34.1B	29.1b	37.2b	33.1B
Mean	3.63B	4.25A		35.3B	43.0A		34.3B	41.8A	
LSD for G	0.3783			5.8271			5.6636		
LSD For T	0.7565			11.654			11.327		
LSD for G × T	1.0699			16.482			16.019		

Table 10. Root length for both genotypes at three leaf, anthesis and maturity.

root length at anthesis stage. Maximum root length was recorded for T7 (54.8 cm) followed by T3 (51.7 cm) whereas, minimum root length was recorded for T1 (35.13 cm) at anthesis stage. There was 49% difference between T7 and T1 for root length. Similarly, the interactive effects were highly variable at anthesis stage. Highest root length (69.2 cm) was recorded for NARC-2009 under T7 while lowest root length (29.9 cm) was recorded for Sehar-06 under T7. Both the wheat genotypes varied considerably for root length at maturity stage (**Table 10**). NARC-2009 accumulated maximum root length (41.8 cm) while Sehar-06 accumulated minimum root length (34.3 cm). There was 18% difference among both the genotypes for root length accumulation. In the same way all the treatments varied significantly for root length. Highest root length was recorded was recorded for T7 (53.2 cm) followed by T3 (50.2 cm) and lowest root length was recorded for T5 (27.1 cm). There was 49% difference between T7 and T5. Similarly, the interactive effects were also significantly different at 1% P level for root length accumulation at maturity stage. Highest root length was recorded for NARC-2009 under T7 (67.3 cm) while lowest for Sehar-06 under T8 (29.1 cm). In the stress environment the length of roots increased to ensure proper supply of nutrients to the plant body. Phosphorus application enhanced root length to ensure better nutrient supply to the plant body. Our results were in accordance with Fahad and Bano [13] who stated that nutrient enhanced the crop stress tolerance hence help in root elongation. It would be advantageous if we select, screen or improve plants for higher capacity to adapt to mineral stresses. This approach is beneficial in developing countries like Pakistan where capital input resources are limited. Farmers in these countries require nutrient efficient crop cultivars which perform better or do something better than other cultivars when given a considerable amount of mineral nutrient.

4.2.3. Shoot dry weight

Both the genotypes differed considerably for shoot dry weight accumulation (**Table 11**). The results depicted that maximum shoot dry weight was accumulated by NARC-2009 (0.21 g) while minimum shoot fresh weight was accumulated by Sehar-06 (0.14 g) at three leaf stage. There was 32% variation among both the genotypes for shoot dry weight accumulation at three leaf stage. On the other hand, all the treatments exhibited significant difference for shoot dry weight at three leaf stage. Highest shoot dry weight was recorded for T7 (0.25 g) while lowest shoot dry weight was recorded by T4 (0.11 g). There was 57% difference among higher and lower treatments. In the same way, the interactive effects varied potentially. Highest shoot dry weight recorded for NARC-2009 (0.29 g) under T7 while lowest shoot dry weight was recorded for Sehar-06 under T4 (0.08 g). There was 61% difference among maximum and minimum shoot dry weights. Genotype NARC-2009 and Sehar-06 did not varied potentially for shoot dry weight at anthesis stage (**Table 11**). Whereas, all the treatments varied noticeably for shoot dry weight at anthesis stage. Maximum shoot dry was recorded for T7 (1.59 g) followed by other treatments except T4 which accumulated minimum shoot dry weight (1.28 g) at anthesis stage. There was 19% difference between T7 and T4 for shoot dry weight at anthesis. Similarly, the interactive effects were highly variable at anthesis stage. Highest shoot dry weight (1.66 g) was recorded for NARC-2009 under T7 while lowest shoot dry weight (1.23 g) was recorded for Sehar-06 under T4. There was 25% difference among highest and lowest shoot dry weight under all the treatments for both the genotypes. Both the genotypes did not differ considerably for shoot dry weight accumulation at maturity stage (**Table 11**). On the other hand, all the treatments exhibited significant difference for shoot dry weight at maturity stage. Maximum shoot dry weight was accumulated for T7 (2.55 g) while minimum shoot dry weight was recorded by T4 (2.06 g). There was 19% difference among higher and lower

Treatments	Three leaf		Mean	Anthesis		Mean	Maturity		Mean
	G1	G2		G1	G2		G1	G2	
T1	0.08c	0.13bc	0.11C	1.30ab	1.42ab	1.36AB	2.09ab	2.28ab	2.18AB
T2	0.11c	0.17a–c	0.14BC	1.44ab	1.57ab	1.50AB	2.30ab	2.51ab	2.40AB
T3	0.14bc	0.21a–c	0.18A–C	1.3ab	1.42ab	1.36AB	2.08ab	2.27ab	2.18AB
T4	0.11c	0.17a–c	0.14BC	1.23b	1.34ab	1.29B	1.97b	2.15ab	2.06B
T5	0.14bc	0.21a–c	0.18A–C	1.28b	1.40ab	1.34AB	2.06b	2.25ab	2.15AB
T6	0.17a–c	0.25ab	0.21AB	1.31ab	1.43ab	1.37AB	2.10ab	2.29ab	2.19AB
T7	0.20a–c	0.29a	0.25A	1.52ab	1.66a	1.59A	2.44ab	2.66a	2.55A
T8	0.17a–c	0.25ab	0.21AB	1.44ab	1.57ab	1.50AB	2.30ab	2.51ab	2.40AB
Mean	0.14B	0.21A		1.35NS	1.48		2.16NS	2.37	
LSD for G	0.0477			0.1321			0.2118		
LSD For T	0.0954			0.2642			0.4236		
LSD for G × T	0.1349			0.3736			0.5991		

Table 11. Shoot dry weight for both genotypes at three leaf, anthesis and maturity.

treatments. In the same way, the interactive effects varied considerably. Highest shoot dry weight was recorded for NARC-2009 (2.66 g) under T7 followed by all other treatments except Sehar-06 under T4 (1.97 g) fallowed by Sehar-06 under T5 (1.97 g). There was 26% difference among maximum and minimum shoot dry weights. Root signaling influence directly above ground biomass production. With the application of phosphorus roots were able to penetrate deep in the soil to provide better nutrients to the above ground parts. Our results were in accordance to Dewal and Pareek, [50] who stated that dry matter production increased by the addition of phosphorus. Similar results were also reported by Swarup and Yaduvanshi, [51] who concluded that fertilization of crop with phosphatic compounds resulted in enhanced dry matter accumulation.

4.2.4. Root dry weight

Balanced plant nutrition encourages above and below ground plant growth development. Both the genotypes differed considerably for root dry weight at three leaf stage (**Table 12**). Genotype NARC-2009 accumulated maximum root dry weight (0.16 g) while Sehar-06 accumulated minimum root dry weight (0.11 g). There was 31% difference among genotypes for root dry weight at three leaf stage. All the treatments were statistically varied for root dry weight at three leaf stage. The highest root dry weight was recorded for treatment T7 (0.195 g) while, lowest root dry weight was recorded for T1 (0.08 g). In the same way, the interactive effects differed considerably for root dry weight under all the treatments for both genotypes at three leaf stage. Maximum root dry weight was accumulated by NARC-2009 under T7 (0.23 g) whereas, minimum root dry weight was accumulated by Sehar-06 under T1 (0.07 g). Both the genotypes did not varied considerably for root dry weight at anthesis stage (**Table 12**). On the other hand, all the treatments varied noticeably for root dry weight at anthesis stage. Maximum root dry was

Treatments	Three leaf		Mean	Anthesis		Mean	Maturity		Mean
	G1	G2		G1	G2		G1	G2	
T1	0.07c	0.09bc	0.08C	1.2ab	1.31ab	1.26AB	1.53ab	1.66ab	1.59AB
T2	0.09bc	0.13a–c	0.11BC	1.32ab	1.45ab	1.39AB	1.68ab	1.83ab	1.76AB
T3	0.11bc	0.16a–c	0.14ABC	1.2ab	1.31ab	1.25AB	1.52ab	1.66ab	1.59AB
T4	0.09bc	0.13a–c	0.11BC	1.14b	1.24ab	1.19B	1.44b	1.57ab	1.51B
T5	0.11bc	0.16a–c	0.14ABC	1.19b	1.29ab	1.24AB	1.50b	1.64ab	1.57AB
T6	0.13a–c	0.19ab	0.17AB	1.21ab	1.32ab	1.27AB	1.54ab	1.68ab	1.61AB
T7	0.16a–c	0.23a	0.19A	1.41ab	1.53a	1.47A	1.79ab	1.95a	1.87A
T8	0.13a–c	0.19ab	0.16AB	1.32ab	1.45ab	1.39AB	1.68ab	1.83ab	1.76AB
Mean	0.12B	0.16A		1.25NS	1.37		1.58NS	1.73	
LSD for G	0.0368			0.122			0.1547		
LSD For T	0.0736			0.2439			0.3095		
LSD for G × T	0.1041			0.3449			0.4376		

Table 12. Root dry weight for both genotypes at three leaf, anthesis and maturity.

recorded for T7 (1.47 g) fallowed by other treatments except T4 which accumulated minimum root dry weight (1.18 g) at anthesis stage. There was 24% difference between T7 and T4 for root dry weight at anthesis. Similarly, the interactive effects were highly variable at anthesis stage for root dry weight at anthesis stage. Highest root dry weight (1.53 g) was recorded for NARC-2009 under T7 while lowest shoot dry weight (1.14 g) was recorded for Sehar-06 under T4. There was 25% difference among highest and lowest root dry weight under all the treatments for both the genotypes. Both the genotypes were not varied potentially for root dry weight at maturity (**Table 12**). In the meanwhile, all the treatments differed significantly for root dry weight at maturity stage. Highest root dry weight was calculated for T7 (1.86 g cm) followed by all other treatments while, lowest was calculated for T4 (1.51 g). There was 19% variation among highest and lowest treatments for root dry weight. Meanwhile, the interactive effects were highly significant at 1% P level for root dry weight. Highest root dry weight was recorded for NARC-2009 under T7 (1.94 g) while lowest for Sehar-06 under T4 (1.44 g).

4.2.5. Root-shoot ratio

Both the genotypes were non-significant for root to shoot ratio at three leaf stage (**Table 13**). Whereas, all the treatments varied noticeably for root to shoot ratio at three leaf stage. Maximum root to shoot ratio recorded for T1 (0.92) while minimum root to shoot ratio calculated for T6 (0.57) at three leaf stage. There was 38% difference between T1 and T6 for root to shoot ratio at three leaf stage. Similarly, the interactive effects were highly variable at three leaf stage for root to shoot ratio at three leaf stage. Highest root to shoot ratio (0.94) was recorded for NARC-2009 under T1 followed by Sehar-06 under T1 (0.90) while lowest root to shoot ratio (0.54 g)

Treatments	RSRT		Mean	RSRA		Mean	RSRM		Mean
	G1	G2		G1	G2		G1	G2	
T1	0.90a	0.95a	0.93A	0.82b	0.66c–e	0.74BC	0.73b	0.59c–e	0.66BC
T2	0.84ab	0.76bc	0.79BC	0.72b–d	0.69cd	0.71BC	0.64b–d	0.63b–d	0.63BC
T3	0.67c–f	0.65c–g	0.66DE	0.76bc	1.05a	0.91A	0.67bc	0.93a	0.81A
T4	0.84ab	0.90a	0.87AB	0.58e–h	0.48hi	0.53D	0.52e–g	0.42gh	0.47D
T5	0.69c–e	0.75b–d	0.72CD	0.55f–h	0.37i	0.46D	0.49fg	0.33h	0.41D
T6	0.54g	0.60e–g	0.57F	0.72b–d	0.61d–f	0.67C	0.64b–d	0.55d–f	0.59C
T7	0.59e–g	0.56fg	0.58EF	0.64d–g	0.96a	0.78B	0.54d–f	0.85a	0.69B
T8	0.63d–g	0.62e–g	0.63EF	0.49gh	0.55e–h	0.52D	0.44fg	0.49e–g	0.47D
Mean	0.71NS	0.72		0.66NS	0.67		0.59NS	0.6	
LSD for G	0.0426			0.041			0.0368		
LSD For T	0.0852			0.082			0.0737		
LSD for G × T	0.1204			0.116			0.1042		

Table 13. Root-shoot ratio for both genotypes at three leaf, anthesis and maturity.

was recorded for Sehar-06 under T6. There was 42% difference among highest and lowest root dry weight under all the treatments for both the genotypes. Both the wheat genotypes did not varied considerably for root to shoot ratio at anthesis stage (**Table 13**). In the meanwhile, all the treatments varied significantly for root to shoot ratio at anthesis stage. Highest root to shoot ratio was recorded for T3 (0.90) and lowest root to shoot ratio recorded for T5 (0.46). There was 48% difference between T3 and T5. Similarly, the interactive effects were also significantly different at 1% P level for root to shoot ratio at anthesis stage. Highest root to shoot ratio was recorded for NARC-2009 under T3 (1.05) followed by NARC-2009 under T7 (0.96) while lowest for NARC-2209 under T5 (0.37). There was 48% difference among highest and lowest root dry weight under all the treatments for both the genotypes at anthesis stage.

Both the genotypes were not different for root to shoot ratio at maturity stage (**Table 13**). In the meanwhile, all the treatments differed significantly for root to shoot ratio at maturity stage. Highest root to shoot ratio was calculated for T3 (0.81) followed by all other treatments while, lowest was calculated for T5 (0.41). There was 49% variation among highest and lowest treatments for root to shoot ratio at maturity stage. Meanwhile, the interactive effects were highly significant at 1% P level for root to shoot ratio. Highest root to shoot ratio was recorded for NARC-2009 under T3 (0.93) fallowed by NARC-2009 under T7 (0.85) while lowest for NARC-2209 under T5 (0.33). There was 64% difference among highest and lowest root dry weight under all the treatments for both the genotypes at maturity stage. Root architecture is a highly plastic and environmentally responsive trait that enables plants to counteract nutrient scarcities with different forging strategies [7]. Root-specific traits such as root system architecture, sensing of edaphic stress and root-to-shoot communication can be exploited to improve resource capture (water and nutrients) and plant development under resource-limited conditions [8].

Treatments\genotypes	Sehar-06	NARC-2009	Mean
T1	8.4ab	9.1ab	8.7AB
T2	9.2ab	10.0ab	9.6AB
T3	8.3ab	9.1ab	8.7AB
T4	7.9b	8.6ab	8.2B
T5	8.2b	8.9ab	8.6AB
T6	8.4ab	9.2ab	8.8AB
T7	9.8ab	10.7a	10.2A
T8	9.2ab	10.0ab	9.6AB
Mean	8.7B	9.5A	
LSD for G	0.7473		
LSD for T	1.6947		
LSD for G × T	2.3966		

Table 14. Spike length for both genotypes at maturity.

4.2.6. Spike length

Spike length of the both wheat genotypes differed considerably due to their genetic characteristics (**Table 14**). The results illustrated that the higher spike length was recorded for the NARC-2009 (9.5 cm) against Sehar-06 (8.7 cm). The difference between both genotypes was 8%. While discussing about treatments, maximum spike length was recorded for T7 (10.2 cm), while the minimum spike length was noticed under T4 (8.2 cm). There was 14% difference among highest and lowest treatments. Similarly, the interactive effect was significant. Highest spike length was recorded for NARC-2009 under T7 (10.7 cm) while lowest spike length was observed for Sehar-06 under T4 (7.89 cm). There was 21% variation for spike length among highest and lowest interactions. Root signaling played a vital role in the development of the good source-sink relationship. Maximum spike length is produced as translocation of more photo-assimilates takes place efficiently from source to sink. Balanced application of P fertilizers and their availability might be another reason of spike length increment. Our findings were in accordance with Dewal and Pareek [50] and Memon [52] who reported increment in spike length with the addition of P fertilizers. Our results were also confirmed by the findings of Hussain [53] who reported increase in spike length due to P addition.

4.2.7. Spikelets per spike

Spikelets per spike of the both wheat genotypes varied noticeably due to their genetic characteristics (**Table 15**). The results depicted that the higher spikelets per spike was observed for the NARC-2009 (2.7) against Sehar-06 (2.5). The difference between both genotypes was 8%. As regards to treatments, maximum spike length was recorded for T7 (2.9), while the minimum spike length (2.4) was noticed under T4. There was 15% difference among highest and lowest treatments. Similarly, the interactive effect was significant. Highest spike length was recorded for NARC-2009 under T7 (3.1) while lowest spikelets per spike were observed for Sehar-06 under T4 (2.3). There was 22% variation for spikelets per spike among highest and lowest interactions. The variation in number of spikelets per spike might be due to balanced

Treatments/genotypes	Sehar-06	NARC-2009	Mean
T1	2.4ab	2.6ab	2.5AB
T2	2.6ab	2.9ab	2.8AB
T3	2.4ab	2.6ab	2.5AB
T4	2.3b	2.ab	2.4B
T5	2.4b	2.6ab	2.5AB
T6	2.4ab	2.6ab	2.5AB
T7	2.8ab	3.1a	2.9A
T8	2.6ab	2.9ab	2.8AB
Mean	2.5B	2.7A	
LSD for G	0.2234		
LSD for T	0.4867		
LSD for G × T	0.6883		

Table 15. Spikelets per spike for both genotypes at maturity.

application of P fertilizers and enhanced availability as well as uptake of phosphorus through root signaling by plants. Another reason might be spike length which consumes available nutrient resources as well as temperature in more proficient way and accumulated photo-assimilates efficiently. As P application and availability support growth and developmental process in plants through root signaling such as photosynthesis, energy storage, transfer, cell division as well as cell elongation so it also promotes spikelets initiation and finally increases number of spikelets per spike. Similar results were reported by Memon [52] who observed a significant increase in number of spikelets per spike by the application of P fertilizers through enhanced root signaling.

4.2.8. Number of grains per spike

Both the genotypes varied potentially for number of grains per spike (**Table 16**). NARC-2009 exhibited maximum number of grains per spike (23.56) than Sehar-06 (21.45). There was 9% difference among both the genotypes for number of grains per spike. All the treatments showed significant difference for number of grains per spike. Highest number of grains per spike was recorded for T7 (26.99) while lowest number of grains per spike was recorded for T4 (20.07). In the same way, the interactive effect was also found significant. Maximum number of grains per spike was recorded for NARC-2009 under T7 (28.21) whereas, minimum number of grains per spike was recorded for Sehar-06 under T4 (19.21). Root signaling played a vital role in enhancing number of grains per spike. By applying phosphorus root signaling enhanced in the crop. Sufficient availability and the uptake of P facilitate the crop to grow more rapidly and it also enables the crop to capture more solar radiations and consequently more number of grains per spike produced. Insufficiency of P undersized the growth of stem as well as whole plant. However, the addition of P encourages the plant growth which results in increase in number of spikelets per spike due to better root signaling. With the increase in number of spikelets per spike, number of grains per spike also increased. The results of present study were in line with Ali et al. [54] and Dewal and Pareek [50] who observed the reduction in number of grains per

Treatments/genotypes	Sehar-06	NARC-2009	Mean
T1	20.32cd	21.81b–d	21.07BC
T2	22.41a–d	24.42a–d	23.42A–C
T3	20.27cd	22.09a–d	21.19BC
T4	19.21d	20.93b–d	20.07C
T5	20.06cd	21.87b–d	20.97BC
T6	20.85b–d	22.33a–d	21.59BC
T7	25.79a–c	28.21a	26.99A
T8	22.66a–d	26.84ab	24.75AB
Mean	21.45B	23.56A	
LSD for G	2.1023		
LSD for T	4.4173		
LSD for G × T	6.267		

Table 16. Number of grains per spike for both genotypes at maturity.

spike with the reduction in quantity of P applied. Similar results were reported by Poulsen et al. [55] who suggested that P fertilization maximizes number of grains per spike in wheat crop.

4.2.9. Spike weight

Spike weight of the both wheat genotypes differed considerably due to their genetic characteristics (**Table 17**). The results depicted that the higher spike weight was recorded for the NARC-2009 (0.52 g) against Sehar-06 (0.46 g). The difference between both genotypes was 11%. Similarly, all the treatments differed potentially for spike weight. Maximum spike weight was recorded for T7 (0.55 g) followed by T8 (0.53 g), while the minimum spike weight was noticed under T1 (0.43). There was 21% difference among highest and lowest treatments. Similarly, the interactive effect was significant for spike weight. Highest spike weight was recorded for NARC-2009 under T7 (0.57 g) while lowest spike weight was observed for Sehar-06 under T1 (0.41 g). There was 28% variation for spike weight among highest and lowest interactions. Increased spike weight might be due to the adequate accessibility and uptake of P by crop plants. In stressed environment phosphorus played role to enhance root signaling. Due to uptake of P in adequate amount maximum numbers of fertile tillers were produced and the spike length, number of spikelet per spike and grains per spike also increased due to photosynthesis, energy storage, transfer, cell division as well as cell elongation so ultimately it results in increase in grain yield. The findings of current study corroborate the conclusions of Al-Karaki and Al-Omoush, [56], and Mehdi et al. [57] who reported that application of P increases spike weight which ultimately enhanced grain yield. Our results were not in accordance with Somayeh and Bahram [58], who reported enhanced spike weight by addition of phosphorus.

4.2.10. Hundred grain weight

Wheat genotypes due to their genetic behavior differed considerably for hundred grain weight at (**Table 18**). Highest hundred grain weight (4.18 g) calculated for genotype NARC-2009 whereas, lowest hundred grain weight (3.71 g) calculated for genotype Sehar-06. Both the genotypes differed 11% for hundred grain weight. All the treatments varied significantly for hundred grain weight. Highest hundred grain weight (4.38 g) recorded for treatment T7

Treatments/genotypes	Sehar-06	NARC-2009	Mean
T1	0.41i	0.47e–h	0.43E
T2	0.43hi	0.49d–f	0.45DE
T3	0.44g–i	0.49de	0.46DE
T4	0.45f–i	0.51cd	0.48CD
T5	0.47e–g	0.53b–d	0.49BC
T6	0.49de	0.56a–c	0.52AB
T7	0.52b–d	0.57a	0.55A
T8	0.50de	0.56ab	0.53A
Mean	0.46B	0.528A	
LSD for G	0.0149		
LSD for T	0.0298		
LSD for G × T	0.0421		

Table 17. Spike weight for both genotypes at maturity.

Treatments	Sehar-06	NARC-2009	Mean
T1	3.27i	3.74e–h	3.51E
T2	3.41hi	3.91d–f	3.67DE
T3	3.48g–i	3.99de	3.74DE
T4	3.59f–i	4.11cd	3.85CD
T5	3.77e–g	4.22b–d	3.99BC
T6	3.96de	4.40a–c	4.19AB
T7	4.17bcd	4.58a	4.38A
T8	4.01de	4.48ab	4.25A
Mean	3.7125	4.1829	
LSD for G	0.1193		
LSD for T	0.2386		
LSD for G × T	0.3376		

Table 18. Hundred grain weight for both genotypes at maturity.

fallowed by T8 (4.25 g) whereas, lowest hundred grain weight (3.51 g) observed for treatment T1. There was 19% difference among T7 and T1 for hundred grain weight. Similarly, there was significant difference among all the interactive effects at 1% P level. Maximum hundred grain weight observed for genotype NARC-2009 (4.58 g) under T7 whereas, minimum hundred grain weight recorded for Sehar-06 under T1 (3.27 g). There was 28% difference among maximum and minimum interactive effects for hundred grain weight. Grain weight is directly a measure of final productivity of the field crop. Greater the grain weight greater will the economical yield. Phosphorus applications in the stressed environment enhanced root signaling which ultimately enhanced grain weight. The reason of increased hundred grain weight might be due to provision of available phosphates to the plants in sufficient amount. Availability of P encourages root development and stimulates growth at seedling stage, so it promotes the quick establishment of seedling. It also accelerates leaf development and promotes faster growth of shoots and roots. As addition of phosphorus encourages normal growth of plant, ultimately it increased hundred grain weight. Similar results were found by Dewal and Pareek [50] and Memon [52] who observed considerable increase in grain weight in wheat by the addition of phosphorus.

5. Conclusion

Root architecture is a highly plastic and environmentally responsive trait that enables plants to counteract nutrient scarcities with different forging strategies. Root-specific traits such as root system architecture, sensing of edaphic stress and root-shoot communication can be exploited to improve resource capture (water and nutrients) and plant development under resource-limited conditions. The ability of plants to respond appropriately to nutrient availability is of fundamental importance for their adaptation to the environment. These signals trigger molecular mechanisms that modify cell division and cell differentiation processes within the root and have a profound impact on root system architecture. Important developmental processes, such as root-hair formation, primary root growth and lateral root formation, are particularly sensitive to changes in the internal and external concentration

of nutrients. Phosphorus (P) is one of the most vital nutrients needed for wheat production. Phosphorus plays an important role in root growth and builds resistance against abiotic stresses. It functions as one of the major players in process of photosynthesis, nutrient transport, and energy transfer. Drought stress reduces leaf size, stem elongation, root proliferation, as well as, disturbs plant water relations and reduces water use efficiency in plants. The present study conducted in laboratory as well as in polythene bags. In first experiment (screening test), nine wheat genotypes sown in petri dishes using four treatments (control, $PEG_{-0.50}$, $PEG_{-1.48}$ and $PEG_{-2.95}$) as a medium of growth. The data regarding germination percentage, root fresh weight, root dry weight, root length, shoot fresh weight, shoot dry weight and root shoot ratio recorded from experiment one and analyzed statistically. On the basis of stress tolerance two wheat genotypes were selected for next experiment. Genotypes NARC-2009 and Sehar-06 accumulated maximum germination percentage, root length, shoot length, root fresh weight, shoot fresh weight, shoot dry weight and root shoot ratio. So these two genotypes were selected for further experimentation. In experiment # 2 the effect of different treatments of phosphorus and water stress on root signaling checked. The treatments were 5 different levels of P including (P_{30} = 0.26 g/bag, P_{60} = 0.4 g/bag, P_{80} = 0.53 g/bag, P_{100} = 0.66 g/bag and P_{120} = 0.8 g/bag) and three different water levels designated as WFC, W10% < FC and W20% < FC. The data regarding root length, root weight, root-shoot ratio, root length, root fresh weight, root dry weight, root fresh weight: root dry weight, root hair density, root depth and yield and yield parameters collected and analyzed. Among both the genotypes, NARC-2009 performed well compared to Sehar-06. While discussing treatments higher dry matter and yield and yield parameters were recorded under T7 (P_{100}). With the increasing rate phosphorus root and shoot length was increasing linearly up-to P100 then it was declining. So under pot conditions where nutrients are limiting factor higher rate of phosphorus is essential to boost the productivity of the crop through better action of root signaling. Root signaling played important role in the growth and development of wheat crop. Under stressed conditions plant height, root and shoot length, root and shoot fresh and dry weight, yield and yield parameters decreased but in the presence of phosphorus all these parameters increased.

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