EVALUATION OF STAND ESTABLISHMENT AND GROWTH PERFORMANCE OF WHEAT IN RESPONSE TO DIFFERENT WATER POTENTIAL LEVELS

Mohammad Akmal¹*, Muhammad Afzal² and Tadashi Hirasawa³

¹Department of Agronomy, University of Agriculture, Peshawar, Pakistan; ²Department of Soil & Environmental Sciences, University of Agriculture, Peshawar, Pakistan; ³Eco-physiology Lab, Tokyo University of Agriculture and Technology, Japan.
*Corresponding author’s e-mail: akmal_m@hotmail.com

Early growth of a germinated wheat seed was characterized with changes in vermiculite water potentials (Ψw -0.03 to -1.10 MPa) and pots depth (10 to 30 cm). Deionized water was added in vermiculite for a desired Ψw treatment. Germinated seeds of 5-mm radicles were planted in pots and glass boxes. Experiments were conducted in controlled condition in a growth chamber. Periodic samples were taken on each sampling day to measure roots and shoot of young wheat plant. Leaf area was markedly sensitive to decrease in Ψw from -0.03 to -0.60 MPa with no leaf visibility at Ψw -1.10 MPa in 25 days old seedlings. Dry matter (DM) decreased by reducing Ψw, but this reduction in DM was associated to both shoot and roots losses. DM of seed-hull increased by decrease in Ψw. No changes in DM were observed in early 7 days growth at Ψw -0.03 and -0.15 MPa. Seminal roots number did not differ at higher Ψw but markedly decreased at low Ψw. The root length showed a linear reduction by decrease in Ψw from -0.03 to -1.10 MPa. Root branch length also shrank markedly at high (Ψw -0.03 to -0.06) to moderate (Ψw -0.60 to -1.10) decrease in Ψw. Root length to weight ratio was linear but negatively related to decrease in Ψw with a linear positive change with time after the seed transplanting. Osmotic potential and tissue moisture content declined in a linear fashion by the decrease in Ψw for different parts. DM of shoot and roots was observed in exponential fashion to DM of seed-hull and time to the transplanting. A linear but negative relationship was noted for shoot and roots to seed-hull fractional contribution in DM (FCDM). The study suggests marked sensitivity of root and shoot to reduction in Ψw in the early development stages of wheat plant. Reduction in Ψw markedly decreased roots and branch number and their length, which inhibited leaf initiation.

Keyword: Wheat seedlings, water potential, seminal roots, root branch, drought, osmotic potential

INTRODUCTION

Wheat (Triticum aestivum L.), oldest plants in cultivation by the mankind, is extensively planted worldwide due to its adaptation to a range of climates. Population growth, especially in agrarian regions will demand more production over time in the future. Limitation of available water for crops and future expected climate change might increase stress for wheat production in many arid and semi-arid regions of the world (Chen et al., 2012; Akmal et al., 2014). According to an estimate, drought may affect 99 million ha wheat in developing countries and 60 million ha in the developed countries (Rajaram, 2000). Water stress could reduce grain yield with an average loss from 17 to 70% (Nouri-Ganbalani et al., 2009). Although in comparison with other cereals crops e.g. maize, wheat is fairly drought tolerant (Akmal and Hirasawa, 2004). It can successfully be grown with little but well distributed precipitation in early development phase. A small quantity of rain in early wheat growth can results no loss in the grain yield. Crop failure of wheat is mostly reported when soil moisture is insufficient to complete germination and/or acute short for the initial establishment of young a wheat plant in early vegetative development phases. Once the seedling established successfully and passed from seedling to plant stage, it become auto-tropic. Its growth becomes less susceptible to environmental fluctuations while plant is able to evolve mechanism responding to a variety of environmental signals (i.e. soil moisture, light, temperature and gravity etc.). These signals can play significant role in controlling growth mechanism within the plant body. The limited water undoubtedly has a significant impact on plant growth and may cause considerable loss in productivity worldwide (Martin et al., 2006). Growth is results of evapotranspiration (Ca. 200-1000 times of body dry matter) during the plant life cycle (Hasiao and Xu, 2000). It mainly keeps leaf open for adequate CO2 exchange to build photo- assimilates for body maintenance. Under deficient water condition, both leaf and shoot growth is inhibited (Nonami and Boyer, 1990; Chazen and Neumann, 1994) and/or roots elongation is continued even under complete inhibition of shoot (Westgate and Boyer, 1985; Spollen et al., 1993). It may be possible that
roots play a key role in water uptake regulation and maintaining balance of plant water budget (Javot and Maurel, 2002). Nonetheless, regulation of roots water flow properties is still not fully identified at lower water potentials (Aroca et al., 2012). We have noted that length of a seminal root of wheat declined at reduction of the substrate moisture content. This decrease in root length may be due to decrease extensibility and/or increase in yield threshold of roots’ cell wall or may be due to reduction in hydraulic conductivity of root tissue (Akmal and Hirasawa, 2004).

Soil moisture fluctuation affect has been documented very frequently and in detail on plants shoot growth. However, limited information is available on root-growth relationship under the changing moisture on crop early establishment (Saidi et al., 2010). Despite roots study is equally important while it exploits resources (e.g. nutrients and water) for plant growth and maintenance. Realization of high productivity, therefore, depends on adequate partitioning of carbon to root growth for efficient utilization of soil resources (Farooq et al., 2009). At low soil moisture content, adverse effects can be observed on shoot growth and its functions (Gazal and Kubiske, 2004; Hirasawa et al., 1994; Akmal and Hirasawa, 2004). Relatively less sensitivity of roots than shoot under drought is advantageous to plants under drying soil for initial establishment, whereas, young seedling is more vulnerable to drying soil-surface layers. Root growth potential is simple physiological attribute used for measuring seedling quality in a deficit soil moisture condition (Gazal et al., 2004).

Literature on roots and shoot growth under decreasing $\Psi_{w}$ is limited, sometime may also contradict for roots and shoot growth responses with decreasing $\Psi_{w}$. Moreover, drought is becoming an issue for future agriculture production in most parts of the world. Climate change by increased in CO2 may contribute in rise of average air temperature, which may cause water shortage for crop like wheat famous as a rainfed crop (Saidi et al., 2010). It is known that water shortage to plants has resulted economic losses in many regions (Yin et al., 2005). This study, therefore, focused on root growth of wheat seminal roots and their branch behavior in early establishment phases by decreasing in the vermiculite water potentials. In this stage conversion of a seedling to plant is highly critical for survival in field in collaboration with decrease in temperature for the following days to sustain staple food for the future population.

**MATERIAL AMD MATHODS**

**Plant materials and treatments:** Seeds of wheat cv. Bandowase were used for growth in the vermiculite for all experiments conducted at Eco-physiology Lab, Tokyo University of Agriculture and Technology, Japan. Firstly, seeds were washed with 0.25% NaOCl solution for 10 min, rinsed with de-ionized water for a while and placed on wet filter papers in a glass Petri-dish in incubator. The seeds were allowed to germinate at 25°C in dark in an incubator for 30 h. Six germinated seeds of 5-mm radicles length were planted in plastic pots (10.6 x 30 cm) that had already been filled with vermiculite having different water potentials ($\Psi_{w}$). The bottom-end of plastic tube (pot) was sealed a day before filling with 0.5 cm thick card duly wrapped tightly in a two-fold aluminum foil-film. The aluminum foil-film was used to avoid moisture absorbance from treatment and/or protect material inside from outer contaminations during the study. To avoid evaporation from pots, upper end was also sealed tightly with a 0.5 cm thick Styrofoam cover made for with having holes in it to place the germinated seeds for growth in pots. Seedlings after transplanting were allowed to grow in an incubator under the controlled environmental conditions at ±23/17°C, 250 µ mol photon m$^{-2}$ S$^{-1}$ (PAR), 60/80% relative humidity and a photoperiod of 12 h for all experiments.

Experiment 1 was conducted in June, using four $\Psi_{w}$ treatments (-0.03, -0.15, -0.60 and -1.10 MPa) to study wheat development for 25 days growth after germination (Fig. 1 to 7). Experiment 2 was conducted in July, using four $\Psi_{w}$ treatments (-0.03, -0.07, -0.10 and -0.15 MPa) to study high $\Psi_{w}$ response on plant growth for 7 days after germination (Table 1). Experiment 3 was conducted in August, using two $\Psi_{w}$ treatments (-0.03 and -0.15 MPa) and three depths (10, 20, and 30 cm) in response to observe roots and branch growth behavior of wheat plant for 13 days after germination (Table 2). Experiment 4 was conducted in September, using four $\Psi_{w}$ treatments (-0.03, -0.15, -0.60 and -1.10 MPa) focusing moisture and solute content in wheat plant’s parts (i.e. seed-hull, roots and shoot) for 7 days growth after germination. Experiment 1-3 were done in pots as explained earlier while Exp. 4 was conducted in special glass-boxes (700 x 140 x 40 mm) prepared for the study. For $\Psi_{w}$ treatments, vermiculite from Fukushima, Japan was sieved through 2-mm mesh, initially moist with a half strength Hoagland’s solution (Hoagland and Arnon, 1950) to achieve desired the lowest $\Psi_{w}$ (-1.10 MPa). The de-ionized water of known quantity was added in containers for any subsequent higher $\Psi_{w}$ treatments (-0.60, -0.15 and -0.03 MPa). The 10$^{-4}$ M CaCl$_2$ was also equally added in solution to extend water-holding capacity of vermiculite for the study. The sealed containers of different $\Psi_{w}$ treatments were regularly shaken periodically for six days to homogenize substrate moisture content. On the day of transplanting, all pots were first filled with desired vermiculite treatments of known quantity and immediately sealed from top face with a styro-foam cover. Six germinated seeds were placed in holes of each tube and subsequently covered with a centimeter thick layer of the vermiculite of similar $\Psi_{w}$. Seedlings were allowed to grow in growth chamber for the study period.
Table 1. Growth performance of seven days old wheat seedlings to varying water potential levels.

<table>
<thead>
<tr>
<th>Parameters (plant⁻¹)</th>
<th>Vermiculite (Ψ_w) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.03</td>
</tr>
<tr>
<td>Leaf area (cm²)</td>
<td>3.37 a</td>
</tr>
<tr>
<td>FCLA 1 (%)</td>
<td>84.64 a</td>
</tr>
<tr>
<td>FCLA 2 (%)</td>
<td>15.36 a</td>
</tr>
<tr>
<td>Plant DM (mg)</td>
<td>34.27 a</td>
</tr>
<tr>
<td>Seed-hull DM (mg)</td>
<td>15.59 a</td>
</tr>
<tr>
<td>Shoot DM (mg)</td>
<td>11.09 a</td>
</tr>
<tr>
<td>Roots DM (mg)</td>
<td>22.09 a</td>
</tr>
<tr>
<td>Root number</td>
<td>5.22 a</td>
</tr>
<tr>
<td>Root length (mm)</td>
<td>600.30 ab</td>
</tr>
<tr>
<td>Branch number</td>
<td>11.11 a</td>
</tr>
<tr>
<td>Branch length (mm)</td>
<td>59.17 a</td>
</tr>
<tr>
<td>Roots &amp; Branch length (mm)</td>
<td>659.50 ab</td>
</tr>
<tr>
<td>RLWR (mm mg⁻¹)</td>
<td>87.33 a</td>
</tr>
<tr>
<td>Roots volume (ml)</td>
<td>0.99 a</td>
</tr>
<tr>
<td>Roots to shoot ratio</td>
<td>0.69 a</td>
</tr>
</tbody>
</table>

RLWR = Root length to weight ratio; Mean with a common letter in a row are not significant, Tukey’s studentized range (HSD) test (p≤0.05).

Table 2. Water potential levels and pot depths response on growth performance of 13 days old wheat plant in pots.

<table>
<thead>
<tr>
<th>Parameters (plant⁻¹)</th>
<th>Days (d) after germination (n = 18)</th>
<th>Ψ_w (MPa) (n = 18)</th>
<th>Pot’s depth (D) (n = 12)</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>07</td>
<td>13</td>
<td>-0.03</td>
<td>-0.15</td>
</tr>
<tr>
<td>Leaf area (cm²)</td>
<td>2.68b</td>
<td>6.07a</td>
<td>5.99a</td>
<td>2.74b</td>
</tr>
<tr>
<td>FCLA 1 (%)</td>
<td>52.90b</td>
<td>84.94a</td>
<td>64.24b</td>
<td>73.61a</td>
</tr>
<tr>
<td>FCLA 2 (%)</td>
<td>15.06b</td>
<td>44.90a</td>
<td>34.33a</td>
<td>25.52b</td>
</tr>
<tr>
<td>Plant DM (mg)</td>
<td>31.76b</td>
<td>40.20a</td>
<td>37.75a</td>
<td>34.20b</td>
</tr>
<tr>
<td>Seed-hull DM (mg)</td>
<td>16.64a</td>
<td>6.60b</td>
<td>8.82a</td>
<td>14.41a</td>
</tr>
<tr>
<td>Shoot DM (mg)</td>
<td>8.80b</td>
<td>17.00a</td>
<td>15.39a</td>
<td>10.41b</td>
</tr>
<tr>
<td>Roots DM (mg)</td>
<td>6.31b</td>
<td>16.59a</td>
<td>13.54a</td>
<td>9.37b</td>
</tr>
<tr>
<td>FCDM-Seed-hull (%)</td>
<td>52.04a</td>
<td>17.22b</td>
<td>26.12a</td>
<td>43.14b</td>
</tr>
<tr>
<td>FCDM-Shoot (%)</td>
<td>27.95b</td>
<td>42.00a</td>
<td>39.86a</td>
<td>30.09b</td>
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<tr>
<td>FCDM-Roots (%)</td>
<td>20.02b</td>
<td>40.78a</td>
<td>34.02a</td>
<td>26.78b</td>
</tr>
<tr>
<td>Root number</td>
<td>4.70a</td>
<td>4.78a</td>
<td>4.82a</td>
<td>4.76a</td>
</tr>
<tr>
<td>Root length (mm)</td>
<td>560.10b</td>
<td>1068.00a</td>
<td>979.30a</td>
<td>648.20b</td>
</tr>
<tr>
<td>Branch number</td>
<td>10.35b</td>
<td>1481.00a</td>
<td>65.80a</td>
<td>23.08b</td>
</tr>
<tr>
<td>Branch length (mm)</td>
<td>64.70b</td>
<td>1481.00a</td>
<td>1270.00a</td>
<td>275.00b</td>
</tr>
<tr>
<td>Roots -Branch length (mm)</td>
<td>625.00b</td>
<td>2548.00a</td>
<td>2250.00a</td>
<td>923.00b</td>
</tr>
<tr>
<td>RLWR (mm mg⁻¹)</td>
<td>96.00b</td>
<td>146.70a</td>
<td>150.40a</td>
<td>92.33b</td>
</tr>
<tr>
<td>Roots volume (ml)</td>
<td>0.91b</td>
<td>2.48a</td>
<td>2.28a</td>
<td>1.11b</td>
</tr>
<tr>
<td>RSR</td>
<td>0.73b</td>
<td>0.97a</td>
<td>0.83b</td>
<td>0.87a</td>
</tr>
</tbody>
</table>

Mean with a common letter within category in a row are not significant; Tukey’s studentized range (HSD) test (p≤0.05) * (p≤0.001) and NS = Non-significant.

For Experiment 3, same pots were tightly filled with dry vermiculite at marked depth and sealed with a hard plastic cover duly wrapped in twofold water resistant sheets to avoid any kind of roots or moisture infiltration form growth zone. For experiment 4, two germinated seeds were placed in a box and immediately covered with free glass cover to study the \(Ψ_w\) responses for moisture and solute potentials (\(Ψ_w\)) in wheat plant parts. All boxes were placed inclined at 50° from ground in a growth chamber. Desired water potential for a treatment of this study was achieved by adding known volume of de-ionized water in known quantity of vermiculite. We have already established a
relationship for vermiculite water potential by regressing its moisture and Ψ for treatments (Akmal and Hirasawa, 2004).

**Dry matter and leaf area measurements:** Samples of moist vermiculite were collected at start and at every harvest day from 10 and 20 cm depths from tubes and subsequently oven dried at 105°C for about 72 h to determine changes in Ψ. A slight reduction in Ψ of vermiculite during study at a stable rate was observed for all treatments with time after transplanting. In first experiment, four periodic measurements were taken at six days intervals. First sampling was purposely delayed for a day to allow germinated seeds to adjust with varying Ψ treatments. On each sampling day, three uniform plants per pot were selected and examined. Three pots for each treatment were harvested on a sampling day representing three repeats. On a sampling day, bottom and top faces of pots were carefully opened avoiding any kind of disturbances to young plants. Plants with vermiculite stick to roots collected in a tray and washed with running tap water. During washing, all roots were carefully cleaned and separated. Three plants uniform in appearance were selected from a pot for measurements. Roots and shoot were carefully removed from seed-hull (rest of the seed after emergence). All plant parts i.e. shoot, roots, and seed-hull were preserved in soft moist tissues for measurements. Leaf area of each plant was determined with the help of leaf area measuring machine (AAM-9, Hayashi Denko, Tokyo, Japan). Fractional contribution of leaf area (FCLA) for leaf at nodal position 1 and 2 of the total leaf area was calculated as ratio of the respective leaf in total plant leaf area on a respective sampling day. Dry matter (DM) was determined by oven drying samples at 80°C for not less than 48 h. Oven dried samples of shoots, roots and seed-hulls were separately weighed on an analytical balance. Likewise, fractional contribution of dry matter (FCDM) in total mass of plant organs was estimated as ratio of the respective parts dry matter in total plant DM in percent.

**Root number, length and volume measurements:** To measure the seminal root number, branches and their length, all roots of a treatment were arranged in a plastic tray, which was already bedecked with six-ply soft tissues-sheets covered with an addition two-ply black polyester fiber sheet (BDK, Yunchika, Tokyo, Japan). The material in tray was retained fully moist with de-ionized water facilitating individual root and branch segregation through water for further measurements. On arranging all roots and branches of a treatment in proper order, photographs were taken and roots materials were collected in labeled bags for further measurement of dry matter. Roots photographs were subsequently analyzed through a computer software image analysis program (SigmaScan, Jandel Scientific Software, USA) for root length, branch length and their number. Average root and branch lengths were estimated. The root to shoot ratio (RSR) was derived by dividing weight of roots on shoot excluding seed-hull. Roots volume was measured for rest of the three plants of a tube. Clean roots were immersed in known quantity of water in a graduated beaker and displacement of water was measured as root volume for a treatment. Roots, shoots and seed-hull samples were separately oven dried in bags at 80°C to determine their dry mass.

**Moisture content and solute concentration:** On sampling day, open face of the glass box was carefully removed in a moisture-saturated chamber (Akmal and Hirasawa, 2004). Roots were excised with a sharp razor from shoot and seed-hull. All three parts of a plant were separately collected in an airtight glass bottles working within a humid chamber. The part’s moisture contents were determined by subtracting differences in fresh matter of a plant parts and oven dried at 80°C for not less than 48 h. For measurements of the solute concentration (Ψo), samples of plant parts were immediately frozen in liquid N and stored in a freezer at -80°C. On the day of measuring Ψo of plant parts, samples were de-frozen at room temperature (25°C) for about 30 min. The solute potential was determined directly by placing each plant part in a separate chamber of a thermocouples psychrometer (Akmal and Hirasawa, 2004). Osmotic potential of plant parts (i.e. roots, shoot and seed-hull) was measured by an isopiestic technique with a thermocouple psychrometer (Boyer and Knippling, 1965).

**Statistical analyses:** For comparing differences in plant parts, leaf area, roots and branch number and length, roots shoot ratio and their interactive effects, we calculated a combined ANOVA in SAS (SAS Institute, 2008). Tukey’s studentized range (HSD) test was used to compare responses of the treatments (p<0.05).

**RESULTS**

**Leaf area:** Leaf area (cm²) of wheat plants was significantly decreased with the decrease in water potential (Fig. 1). Highest leaf area was recorded at Ψw -0.03 MPa, followed by a significant (p<0.001) decrease in Ψw -0.15 and Ψw -0.60 MPa (Fig. 1a). Regarding subsequent plant samplings with age, the leaf area was increased linearly between 7 and 19 d after transplanting with a slight increased from 19 to 25 d after transplanting (Fig. 1b). Interactive effect of varying Ψw and sampling interval showed the highest leaf area for Ψw -0.03, followed by Ψw -0.15 MPa with a significant increase for every subsequent sampling with similar fashion but far lower values for Ψw -0.60 MPa (Fig. 1c). Total leaf area of Ψw -0.03 and -0.15 MPa increased moderately in a linear fashion between 7th and 19th d after the transplanting but with a relatively slower rate thereafter from 19th to 25th d after transplanting. Treatment Ψw -0.60 MPa showed a small fraction of the total leaf area on 19th d after transplanting with
Wheat response to various water potentials

Figure 1. Different water potentials effect on leaf area (cm²) of a young wheat plant [a] for 25 d after transplanting a germinated seed [b]. The interaction of treatments \( \Psi_w \times \) time after transplanting is also shown [c]. The inset figures show fraction of total leaf area (FCLA) for leaf 1 and 2. Letters (a, b & c) indicate statistically significance (\( p \leq 0.001 \)) difference using HSD test.

an almost linear increment on 25\(^{th} \) d after transplanting. The lowest \( \Psi_w = -1.10 \) MPa was unable to show any leaf area in 25 d growth after the transplanting. Moderate reduction in vermiculite \( \Psi_w = -0.3 \) and -0.015 MPa (Table 1) or pot depths (10 to 30 cm) did not show any significant (\( p \leq 0.05 \)) changes in wheat plant leaf area (Table 2). Inset figures in box (Fig. 1a) showed fraction of total leaf area (FCLA) for leaf 1 and 2. Treatment \( \Psi_w = -0.15 \) MPa showed the highest (\( p \leq 0.001 \)) FCLA for leaf 1, followed by slight (\( \Psi_w = -0.03 \) MPa) to moderate (\( \Psi_w = -0.06 \) MPa) decrease approaching to zero (\( \Psi_w = -1.10 \) MPa). The FCLA for leaf 2 was non-significant (\( p \leq 0.05 \)) for treatment high \( \Psi_w = (0.03 \) and -0.15 MPa) but decreased for medium \( \Psi_w = (-0.60 \) MPa) with zero at the lowest \( \Psi_w = (-1.10 \) MPa). While averaged across \( \Psi_w \), FCLA for leaf 1 was the highest at 7\(^{th} \) d after transplanting and significantly (\( p \leq 0.001 \)) decreased at 13th d after the transplanting. FCLA remained unchanged (\( p \leq 0.05 \)) from 13\(^{th} \) to 19\(^{th} \) d after the transplanting with a significant decreased at 25\(^{th} \) d (Box Fig. 1b). The FCLA for leaf 2 was lowest at 7th d after transplanting, increased (\( p \leq 0.05 \)) at 13th with no further change at 19\(^{th} \) d after transplanting. It was recorded the maximum (\( p \leq 0.05 \)) at 25\(^{th} \) d after transplanting. Interaction (\( \Psi_w \times \) samplings) showed a reduction in FCLA for leaf 1 which was strong (7\(^{th} \) and 13\(^{th} \)) to moderate (13\(^{th} \) to 25\(^{th} \)) for \( \Psi_w = -0.03 \) and -0.15 MPa (Box in Fig. 1c). FCLA for leaf 2 increased (7\(^{th} \) to 13\(^{th} \)) with a trivial decrease (13\(^{th} \) to 25\(^{th} \)) for \( \Psi_w = -0.03 \) and -0.15 MPa. FCLA for \( \Psi_w = -0.60 \) MPa was observed on 19th d after transplanting with decrease (\( p \leq 0.05 \)) for leaf 1 and increase (\( p \leq 0.05 \)) for leaf 2 from 19\(^{th} \) to 25\(^{th} \) d after transplanting. FCLA for leaf 1 and 2 did not influence with changes in \( \Psi_w \) (Table 1) or depths (Table 2).
Dry matter (DM): Maximum plant DM was observed at \( \Psi_w = -0.03 \) MPa, which significantly (\( p \leq 0.05 \)) decreased by decreasing \( \Psi_w \) to -0.15 and -1.10 MPa (Fig. 2a). The minimum plant DM was observed for \( \Psi_w = -0.06 \) MPa. Total plant DM did not change (\( p \geq 0.05 \)) with minor changes in \( \Psi_w \) from -0.03 to -0.15 MPa (Table 1) or altering pot depth from 10 to 30 cm (Table 2). For individual plant parts, the DM of a seed-hull increased by reducing \( \Psi_w \) from -0.03 to -1.10 MPa. Seed hull DM for \( \Psi_w = -0.03 \) and -0.15 MPa was lower but did not differ (\( p \geq 0.05 \)) from each other, showed a significant increase for \( \Psi_w = -0.60 \) with a further significant increase for \( \Psi_w = -1.10 \) MPa. Contrary to the seed hull DM, plant shoot and roots DM decreased (\( p \leq 0.001 \)) with a comparable fashion by decreasing \( \Psi_w \) from -0.03 to -1.10 MPa. However, slight changes in \( \Psi_w \) from -0.03 to -0.15 MPa (Table 1) or in pot’s depth (10 to 30 cm) did not show any statistical differences in shoot and/or roots DM (Table 2). Total plant DM did not change (\( p \geq 0.05 \)) between 7 and 13 d after transplanting, but did increase significant (\( p \leq 0.05 \)) at 19 and 25 d after transplanting (Fig. 3b). Seed hull DM decreased (\( p \leq 0.05 \)) between 7 and 19 d with a non-significant changes thereafter between 19 and 25 d after transplanting. Both roots and shoot DM showed a significant (\( p \leq 0.05 \)) increment for every subsequent sampling from 13 to 25 d after transplanting. Moderate changes in \( \Psi_w \) did not show significant (\( p \geq 0.05 \)) effect in seed hull, shoot and roots DM (Table 1) or by changing pot’s depth (Table 2). Interaction (\( \Psi_w \times \) samplings) showed highest plant DM for \( \Psi_w = -0.03 \), followed by -0.15, -0.60 and -1.10 MPa (Fig. 2c). Averaged across \( \Psi_w \), plant DM remained almost stable (\( p \geq 0.05 \)) for 7 and 13 d. with linear fashion growth for 13 and 25 d after transplanting for all parts.

Figure 2. Different water potentials effect on dry matter (mg) of young wheat plant and parts [a] for 25 d growth after transplanting a germinated seed [b]. The interactions of treatment \( \Psi_w \times \) time after transplanting are also shown [c] for total plant, seed-hull, shoot and roots in separate boxes. Letters (a, b, c, & d) indicate statistically significance (\( p \leq 0.001 \)) difference using HSD test.
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Figure 3. Different water potentials effect on plant parts fractional contribution in total dry matter (FCDM) of a young wheat plant [a] for 25 d growth after transplanting a germinated seed [b]. The interactions of treatment $\Psi_w \times$ time after transplanting is also shown [c] for seed-hull [c1], shoot [c2] and roots [c3]. Letters (a, b & c) indicate statistically significance ($p \leq 0.001$) difference using HSD test.

$\Psi_w$ which can be expressed with slopes of regressions i.e. 2.84, 2.03, and 0.70 ($r^2 = 0.99$) for $\Psi_w$ -0.03, -0.15, and -0.60 MPa, respectively. Seed-hull DM remained almost stable for $\Psi_w$ -1.10 MPa from 7 to 25 d after transplanting (Fig. 2d). It decreased at a stable rate for $\Psi_w$ -0.60 MPa from 7 to 19 with no change ($p \geq 0.05$) from 19 to 25 d after transplanting. Seed hull DM for $\Psi_w$ -0.15 and -0.03 MPa were non-significant ($p \leq 0.05$). It was initially decreased (7 and 13 d) and then remained stable (13 to 25 d) after transplanting. Shoot DM was maximum at $\Psi_w$ -0.03 MPa and significantly ($p \leq 0.05$) increased at every subsequent sampling date, followed by $\Psi_w$ -0.15 MPa with marked to moderate increases in every subsequent samplings as compared to $\Psi_w$ -0.03 MPa (Fig. 2e). Shoot DM in $\Psi_w$ -0.60 MPa also increased but with far lower values from $\Psi_w$ -0.15 MPa from 7 and 25 d after transplanting. Shoot DM of $\Psi_w$ -1.10 MPa remained almost constant for 7 to 25 d after transplanting. Likewise, roots DM of $\Psi_w$ -0.03 and -0.15 MPa increased in a similarly fashion for 7 and 13 d after transplanting, differed moderate at 19 to marked at 25 d after the transplanting (Fig. 2f). Root DM was lower for $\Psi_w$ -0.60 MPa at 13 d after transplanting with a linear increase from 13 to 25 d after transplanting. Root DM in $\Psi_w$ -1.10 MPa was almost constant for 25 d growth. Fractional contributions of parts dry matter in total plant dry matter (FCDM) showed mild ($\Psi_w$ -0.03 to -0.15 MPa) to marked ($\Psi_w$ -0.60 to -1.10 MPa) increases in present study (Fig. 3a). Seed hull FCDM under moderate reduction in $\Psi_w$ did not vary (Table 1). Likewise it did not influence by altering pot depths (Table 2). Contrary to the seed hull, Shoot and root FCDM decreased with decrease in $\Psi_w$. A consistent reduction ($p \leq 0.05$) in shoot FCDM was recorded for $\Psi_w$ -0.03 to -1.10 MPa but roots did not show changes in $\Psi_w$ -0.03 and -0.15 MPa. FCDM decreased ($p \leq 0.05$) thereafter for each reduction in $\Psi_w$. Shoot and roots FCDM at moderate reductions in $\Psi_w$.
was not influenced (Table 1) but roots FCDM decreased (p<0.05) when pot-depth limited from 30 to 10 cm (Table 2). Regardless of \( \Psi_w \), seed-hull FCDM decreased (p<0.05) for each subsequent sampling (7 to 25 d) after transplanting (Fig. 4b). Shoot FCDM showed increment (p<0.05) from 7 to 19 d after transplanting and remained non-significant thereafter. Nonetheless, roots FCDM showed increments (7 to 25 d) after transplanting. Interaction (\( \Psi_w \times \text{samplings} \)) revealed marked decreases in seed-hull FCDM (7 to 13 d) for \( \Psi_w \)-0.03 and -0.15 MPa, with further minor losses (19 and 25 d) after transplanting (Fig. 4c). FCDM for seed hull (\( \Psi_w \)-0.60 MPa) was obviously declined for each sampling (7 to 25 d) after transplanting but at slow rates than the \( \Psi_w \)-0.03 & -0.15 MPa. Negligible loss observed in seed-hull FCDM from 7 to 25 d after transplanting for \( \Psi_w \)-1.10 MPa. Roots FCDM increased moderate (7 to 13 d) to marked (13 to 25 d) for \( \Psi_w \)-0.03 and -0.15 MPa (Fig. 3d). Roots FCDM for \( \Psi_w \)-0.60 MPa was lower that \( \Psi_w \)-0.03 and -0.15 MPa but showed mild (7-13 d) to marked (13 to 25 d) increases after the transplanting. Roots FCDM at \( \Psi_w \)-1.10 MPa remained almost stable for 25 d growth after transplanting. Shoot FCDM increased (7 to 13 d) at \( \Psi_w \)-0.03 than -0.15 MPa in first week of transplanting (7 to 13 d) with a slight reduction thereafter (13 to 25 d) with slightly higher readings for \( \Psi_w \)-0.03 than -0.15 MPa (Fig. 3e). Shoot FCDM for \( \Psi_w \)-0.60 MPa showed marked increment (7 to 19 d) after transplanting with almost stable rates for 19 to 25 d after transplanting. Shoot FCDM for \( \Psi_w \)-1.10 MPa was observed almost stable for 25 d growth after the transplanting.

**Root length and number:** The seminal root length (mm) and number under \( \Psi_w \) treatments is shown in Figure 4. A strong (\( \Psi_w \)-0.03 to -0.60 MPa) to moderate (\( \Psi_w \)-0.60 to -1.10 MPa) reduction occurred in the root length when \( \Psi_w \) reduced (Fig. 4a). By averaging across \( \Psi_w \) treatments, roots length showed consistent significant increases from 7 to 25 d after transplanting (Fig. 4b). Moderate reduction in treatments \( \Psi_w \) showed no change in roots length for -0.03 to -0.11 MPa, however, root length of -0.11 and -0.15 MPa also did not differ statistically (Table 1). Similarly, by decreasing pot length from 30 to 20 cm did not show any change (p<0.05) in root length but did reduce root length thereafter from 20 to 10 cm depth (Table 2). Interactive effect of treatments (\( \Psi_w \times \text{samplings} \)) revealed the highest roots length for \( \Psi_w \)-0.03 MPa with a consistent marked increment on every next samplings (Fig. 4c). Treatment \( \Psi_w \)-0.15 MPa did not differ

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Different water potentials effect on root length (mm) of a young wheat plant [a] for 25 d growth after transplanting a germinated seed [b]. Interactions of treatments \( \Psi_w \times \text{time after transplanting} \) is also shown [c]. The inset figures show root number and the interactions showed separately [d]. Letters (a, b & c) indicate statistically significance (p<0.001) difference using HSD test.
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than $\Psi_w$ -0.03 MPa within 7 d after transplanting but did show a substantive increase for every next sampling. However, differences between $\Psi_w$ -0.03 and -0.15 MPa extended wider from 13 to 25 d after transplanting. Nonetheless, root length in $\Psi_w$ -0.60 MPa was recorded far below than $\Psi_w$ -0.15 MPa for samplings after transplanting. Root length of treatment $\Psi_w$ -1.10 MPa remained stable for all samplings for 25 d after transplanting. The inset Figure 4 shows root number of wheat plant. The root number at $\Psi_w$ -0.03 and -0.15 MPa did not differ statistically; however, declined considerably for $\Psi_w$ -0.06 and -1.10 MPa (Box in Fig. 4a). By averaging across $\Psi_w$ treatments, root number did not change between 7 and 25 d after transplanting (Box in Fig. 4b). Interaction of treatments ($\Psi_w$ x samplings) showed higher root number for the high ($\Psi_w$ -0.03 and -0.15) than low ($\Psi_w$ -0.60 and -1.10) MPa for all samplings (Fig. 4d). However, root number did not show any change (p≤0.05) between the high and low $\Psi_w$ from 13 to 25 d after transplanting. Root number did not show any change under the moderate reduction in $\Psi_w$ (Table 1) and/or altering pot depth (Table 2).

Branch length and number: Branch length (mm) of wheat plant seminal roots (BL) is shown in Fig. 5 and their number in the inset boxes. The BL showed a marked (p≤0.001) decrease when vermiculite $\Psi_w$ reduced from -0.03 to -1.10 MPa (Fig. 5a). By averaging across $\Psi_w$, BL showed a modest to marked increments for 7 to 13 and 13 to 25 d after transplanting, respectively (Fig. 5b). Moderate reduction in $\Psi_w$ -0.03 and -0.15 MPa did not show (p≤0.05) any changes in BL (Table 1). Similarly a non-significant effect in BL was noted for different pot depths (Table 2). The interactive effect of treatments ($\Psi_w$ x samplings) showed moderate increase in BL for all $\Psi_w$ treatments with higher for $\Psi_w$ -0.03, followed by -0.15, with lowest for -0.06 MPa between

![Figure 5](image-url)

**Figure 5.** Different water potentials effect on branches length (mm) of a young wheat plant [a] for 25 d after transplanting a germinated seed [b]. The interactions of $\Psi_w$ and time after transplanting are also shown [c]. The inset figures show root number and interactions are shown separately [d]. Letters (a, b & c) indicate statistically significance (p≤0.001) difference using HSD test.
7 and 13 d after the transplanting (Fig. 5c). However, marked increments were noted in BL for every next sampling on 19 and subsequently on 25 d after transplanting with much higher readings for \( \Psi_w \) -0.03, followed by \( \Psi_w \) -0.15 and far lower than \( \Psi_w \) -0.60 MPa. Treatment \( \Psi_w \) -1.10 did not show any BL in 25 d after transplanting. The branch number declined linearly between \( \Psi_w \) -0.03 and -0.60 MPa (Box in Fig. 5a). Root branch number significantly increased for every subsequent sampling (Box in Fig. 5b). Treatment \( \Psi_w \) -1.10 MPa did not show any branch number on root. Moderate reduction in \( \Psi_w \) between -0.03 and -0.11 MPa (Table 1) and variations in pot depth from 30 to 10 cm (Table 2) did not show any changes in seminal root branch number. Root branch number with time showed almost linear trends for different \( \Psi_w \) treatments (Fig. 5d). A significant moderate to marked increases were observed in branch number of \( \Psi_w \) -0.03 and -0.15 MPa for 7 to 13 and 13 to 25 d after transplanting respectively. Contrary to that, \( \Psi_w \) -0.60 MPa showed relatively a stable increment for all four samplings during 7 and 25 d after the transplanting.

**Total root length and RLWR:** Total roots length (mm) including branches (TRL) to their weight (mg) ratio (RLWR) under different \( \Psi_w \) is expressed in Fig. 6. The TRL markedly decreased when \( \Psi_w \) dropped from -0.03 to -0.60 MPa approaching close to zero for \( \Psi_w \) -1.10 MPa (Fig. 6a). Irrespective of \( \Psi_w \) treatments, almost a linear increased \((p \leq 0.001)\) was seen in TRL from 7 to 25 d after the transplanting (Fig. 6b). Slope of increment was 304.71 (mm) with a strong positive relationship \((r^2 = 0.98)\). TRL did not influence under moderate reduction in \( \Psi_w \) -0.03 and -0.11 but did decrease in \( \Psi_w \) -0.15 MPa (Table 1). Pot depth did

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**Figure 6.** Different water potentials effects on total length of roots and braches (mm) of a young wheat plant [a] for 25 days after transplanting a germinated seed [b]. The interactions of \( \Psi_w \) and time after transplanting are also shown [c]. The inset figures show root number and interactions are shown separately [d]. Letters (a, b & c) indicate statistically significance \((p \leq 0.001)\) difference using HSD test.
not show any significant difference in TRL (Table 2). The interactive effect of treatments revealed relatively stable (7 to 13 d) to marked increments in TRL for 13 to 25 d after the transplanting (Fig. 6c). Rate of TRL increments were observed relatively faster in $\Psi_w$ -0.03, to marked in $\Psi_w$ -0.15 MPa. TRL increased at a stable rate in $\Psi_w$ -0.60 MPa from 13 to 25 d after transplanting. The RLWR (mm mg⁻¹) showed almost a linear reduction by decrease in $\Psi_w$ from -0.03 to -1.10 MPa (Box in Fig. 6a). While averaging across $\Psi_w$, RLWR markedly increase with plant age from 7 to 19 d after transplanting with a non-significant change thereafter from 19 to 25 d after transplanting (Box in Fig. 6b). Moderate changes in $\Psi_w$ (Table 1) or pot depth (Table 2) did not differ (p ≤ 0.05) RLWR of wheat plant. Treatment $\Psi_w$ with sampling interaction revealed higher RLWR in $\Psi_w$ -0.03, followed by $\Psi_w$ -0.15 and $\Psi_w$ -0.60 MPa with lowest for $\Psi_w$ -1.10 MPa in all samplings during 25 d growth after transplanting (Fig. 6d). RLWR in $\Psi_w$ -0.03 MPa revealed marked (7 to 19 d) to stable increase (19 to 25 d) while in $\Psi_w$ -0.15 MPa a more or less linear increase for 25 d after the transplanting. Contrary to that RLWR increased linearly for 7 to 19 d after transplanting but declined thereafter from 19 to 25 d after transplanting for $\Psi_w$ -0.60 MPa. A very nominal increase observed in $\Psi_w$ -1.10 MPa for 25 d growth after the transplanting in RLWR.

**Root volume and ratio:** Root volume (ml) declined markedly in a linear fashion when $\Psi_w$ decreases from -0.03 to -0.60 MPa but thereafter a moderate reduction was observed in the root volume with a further decreased in $\Psi_w$ from -0.60 to -1.10 MPa (Fig. 7a). By average across $\Psi_w$, [Figure 7. Different water potentials effects on roots volume (ml) of a young wheat plant [a] for 25 d after transplanting a germinated seed [b]. The interactions of $\Psi_w$ and time after transplanting are also shown [c]. The inset figures show root roots to shoot ratio and the interactions are shown separately [d]. Letters (a, b & c) indicate statistically significant (p ≤ 0.001) difference using HSD test.]
root volume showed a marked increment from 7 to 13 d after transplanting but with a moderate decrease between 19 and 25 d after transplanting (Fig. 7b). The roots volume (ml) did not change either with slight variations in $\Psi_w$ from -0.03 and -0.11 or $\Psi_w$ -0.07 and -0.15 MPa (Table 1) and/or limiting pot-depth from 30 to 10 cm (Table 2). Interaction of treatments $\Psi_w \times$ time after transplanting showed linear increase for $\Psi_w$ -0.03 and -0.15 MPa from 7 and 19 d with a moderate reduction thereafter from 19 to 25 d after transplanting (Fig. 7c). Root volume of $\Psi_w$ -0.60 and -1.10 MPa increased with a very slow and stable rate between 7 and 25 d after transplanting. Root volume increased very slowly in $\Psi_w$ -1.10, relatively mild in $\Psi_w$ -0.60, to high in $\Psi_w$ -0.15 to the highest in $\Psi_w$ -0.03 MPa for 25 d growth. The inset Fig. 8 shows root to shoot ratio (RSR). RSR increased when $\Psi_w$ decreased from $\Psi_w$ -0.03 to -0.06 MPa with a further reduction thereafter from $\Psi_w$ -0.06 to -1.10 MPa (Box in Fig. 7a). RSR between 7 and 25 d after transplanting did not differ (p<0.05) statistically (Box in Fig. 7b). Moderate reductions in $\Psi_w$ (Table 1) or changing pot depth (Table 2) did not influence RSR. Interaction of $\Psi_w$ and time after transplanting showed an increase in RSR for all $\Psi_w$ treatments from 7 to 25 d after transplanting (Fig. 7d). RSR in $\Psi_w$ -0.03 MPa was the lowest and linearly increased with time after transplanting, followed by a similar moderate increase with time for $\Psi_w$ -0.15 MPa. Irrespective of day 7, RSR in $\Psi_w$ -0.60 MPa was observed the highest between 13 and 26 d after transplanting. RSR in $\Psi_w$ -1.10 remained almost stable from 7 to 13 d after transplanting with a sudden decline at 25 d after the transplanting.

**Parts osmotic potential and moisture content:** Data showed that $\Psi_o$ decreased by decreasing vermiculite $\Psi_w$ in the plant parts, but with different rates (Fig. 8a). Among the plant parts, seed-hull showed the lowest $\Psi_o$, followed by shoots and the highest for roots at every $\Psi_w$ treatment. Nonetheless, decreased in $\Psi_o$ against reduction in treatment’s vermiculite $\Psi_w$ was observed in a linear fashion of a plant parts and can be estimate with a regression slope (b). The figures suggest slope values of 1.78 (r²=0.91) for seed-hull, 0.77 (r² = 0.99) for shoot and 0.71 (r² = 0.95) for roots against reductions in $\Psi_w$ (MPa). A decrease in moisture contents (%) was also observed in plant parts for seven days growth after the transplanting from a high to low $\Psi_w$ treatments (Fig. 8b). Figure showed a reduction in moisture contents with decreasing $\Psi_w$ in all parts but with different rates in seed-hull, roots and shoot (Fig. 8a). The seed-hull showed low moisture contents than roots and shoots at all $\Psi_w$ treatments with almost similar values for roots and shoots. The moisture contents decreased in a stable rate in different parts against decrease in the substrate $\Psi_w$ that could be estimate from slopes of linear regression. We estimated slope values 15.36 (r² =0.86) for seed-hull, 6.89 (r² = 0.93) for roots and 9.31 (r² = 0.89) for shoot over a reduction in $\Psi_w$.

**Plant growth dynamics:** Irrespective of vermiculite water potentials treatments, both shoot and roots dry matter showed exponential responses with the seed-hull dry matter (Fig. 9a). The relationships of both the shoot and roots with seed-hull were strongly positively correlated. Likewise, both the shoot and roots fractional dry matter showed a negative linear relationship with seed-hull fractional dry matter (Fig. 9b). As
substrate water potential decreased, the FCDM showed an increase in seed-hull and hence decrease both shoot and roots FCDM. While averaging across different water potential treatments, total root length of wheat plant showed an exponential growth with plant root to shoot ratio (Fig. 9c). Similarly, irrespective of different water potentials treatments, total plant roots length showed a linear relationship with root length to weight ratio (Fig. 9d).

**DISCUSSION**

We observed marked reductions in the leaf area, plant DM, plant roots and shoots DM, seminal roots length, branch length of seminal roots and roots volume of 25 d old wheat seedlings at different $\Psi_w$ levels ranging from -0.03 to -1.10 MPa. It indicated that in 25 d of planting both roots and shoots would have shown similar responses in reduction of $\Psi_w$. The results indicated that shoot growth promoted (p<0.05) with increasing moisture content for a germinated seed of wheat that is known as drought tolerant (Saidi *et al.*, 2010). Reduction in $\Psi_w$ for seedling has already been shown mild to marked (p≤0.05) decreases in the leaf area, tiller number, spike length, grain index, seedling’s height and yield (Kramer and Boyer, 1995; Bayoumi *et al.*, 2008). Reduction in the soil $\Psi_w$ has already shown a decrease (p≤0.05) in germination, coleoptile length, shoot and roots’ length, fresh shoot and roots masses in previous experiments (Chandler and Singh, 2008; Khakwani *et al.*, 2011). Plant growing trait has also shown marked sensitivity to changes in soil moisture (Chandler and Singh, 2008). We know that growth is results of cell divisions and cell enlargements and regulations of the cell extension are critical for crop growth and morphology (Smith, 2003). Stress has confined growth by retarding cell division and -extension, especially under
low $\Psi_w$ (Gao et al., 2007) to understand the physiological mechanisms of crop adaptation to low $\Psi_w$ (Riera et al., 2005). The findings of present study clearly indicated that both root and shoot growth was promoted at higher $\Psi_w$ in wheat seedling, which is known as a relatively drought-resistant crop when compared with other cereals e.g. maize. As reported earlier, leaf area decreased (p≤0.05) markedly with reduction in soil water potential (Kramer and Boyer, 1995; Lambers et al., 1998). It is highly sensitive to drought. Nonetheless, growth responses of roots to a reduction in $\Psi_w$ were observed relatively mild than the shoot (Fig. 9). We observed almost similar responses for wheat roots and shoot growth for 25 d by reduction in the substrate $\Psi_w$. Literature also confirmed that healthy seeds produced healthy crop stand even in an un-favorable environment (Haque et al., 2007; Kalakanavar et al., 1989; Hampton, 1981). It is, therefore, important to understand the responses of $\Psi_w$ for germination and thereafter seedling conversion to a healthy plant (Saidi et al., 2010; Mian and Nafziger, 1992) for optimum productivity. Mostly in arid and semi-arid regions, wheat faced early drought stress that mainly induced emergence and/or mott probably the early seedling growth (Bouazziz and Hicks, 1990). Water shortage at this stage of the crop growth has a serious concern for germination and thereafter the crop stand establishment if associated together with low temperature of the following phases of crop development. No doubt germination markedly affected adversely by drought in soil but the critical lower limit of germination for the external water potential vary among genotypes (Pratap and Sharma, 2010). Both seed size and post emergence environmental conditions may interact with moisture and/or $\Psi_w$ for wheat seedling early growth. Our findings of increased in roots and shoot DM by increasing $\Psi_w$ agree with published literature (Gazal et al., 2004; Saidi et al., 2010). However, the lowest treatment (e.g. $\Psi_w$ -1.10 MPa) was unable to produce any shoot and/or roots DM, which shows that a germinated seed of wheat crop in $\Psi_w$ -1.10 MPa is unable to sustain growth if faced by drought right at germination. Likewise, FCLA for leaf 1 and 2 is interesting estimation of seedling establishment and has showed a similar reduction (p≤0.05) by decrease in substrate $\Psi_w$. As reported earlier, leaf growth is sensitive to losses or changes in substrate $\Psi_w$. It is the initial growth process that affected by decrease in leaf water potential (Bargali and Tewari, 2004). FCLA showed a significant (p≤0.05) decrease by reduction in $\Psi_w$ suggesting that fractional leaf loss is determined primarily by limiting water availability to the seedling early growth (Farooq et al., 2009). Early roots and shoot growth of a young plant are primarily depends on progressive expansion in the plant leaf area in the early phases of development (Mahdidi et al., 2011).

Plant DM was high ($\Psi_w$ -0.03 and -0.15 MPa) to evidently low at low substrate moisture contents ($\Psi_w$ -0.60 and -1.10 MPa). We noticed an increase (p≤0.05) in wheat plant DM at $\Psi_w$ -1.10 MPa due to increase in seed-hull DM. Both shoot and roots DM showed consistent decreases. The literature has also confirmed a consistent reduction in a young plant DM by decreasing moisture contents of the substrate, which mainly associate with marked reduction (p≤0.05) in shoot DM (Hirasawa et al., 2005; Martin et al., 2006) and sporadically in the roots with shoot (Hirasawa et al., 1994; Akmal and Hirasawa, 2004). Seed hull is primary initiator of plan DM, but generally ignored while measuring DM in early stage of a seedling growth. As expected, dry matter of plant increased with time by expansion in roots and shoot DM (Saidi et al., 2010). However, the seed-hull DM showed an increase by decrease in vermiculite $\Psi_w$ confirming that low moisture at $\Psi_w$ -0.60 MPa was not successful transferring all food reserve to the growing plant. Shortage of moisture in substrate at this phase of the crop growth adversely affected seedling establishment, which might be unable to compete in growth to attain the optimum size or volume. Irrespective of the $\Psi_w$ treatments, FCDM of roots and shoot showed a linear decreasing trend against the FCDM of seed-hull (Fig. 9) confirming significance of the seed-hull DM under different $\Psi_w$ treatments. Space availability or depth limitation do not influenced seminal root length and/or branch number but reduction in vermiculite $\Psi_w$ did that affecting the shoot growth and primarily with marked differences in leaf area and FCLA for each developing leaf of the young plant (Boonjung and Fukai, 1996; Sahnow et al., 2004; Akmal and Hirasawa, 2004). Some researchers have also observed an increase in the seminal roots length under mild reduction of substrate $\Psi_w$ due to stimulating cell expansion and elongation (Sharp et al., 2004) but we noted a significant (p≤0.0%) decreases both in root length and branch number that has affected roots volume accordingly when vermiculite moisture decreased (Himmelbauer et al., 2004; Waines and Ehdaiie, 2007). It is quite natural that root elongation in length, branch number expands with initiation, emergence, and growth of lateral roots from the root pericycle and epidermis. Root branch comprises a significant proportion of the root system (Waines and Ehdaiie, 2007; Shah et al., 2012) which if allow to expand optimum under sufficient moisture condition of the substrate (Yoshida et al., 1982), would might have resulted healthy plants right after emergence that would ensure the optimum production. We know that the highest mass or length of a plant roots ensures seedling resistant to stay longer under drought stress conditions if or when temperature is low and seedling is exposed to cope with the unfavorable environments of their surroundings. The study suggests that decreasing $\Psi_w$ of the substrate has shown marked (p≤0.05) changes in roots and shoot growth, which adversely affected the seedling establishment in the
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early development phases of its establishment. The substrate moisture is a fundamental component of transferring assimilates from seed reserve to the growing seedling that is responsible for a healthy crop stand and optimum productivity. Wheat being relatively drought resistant has shown marked differences (p<0.05) for both roots as well as shoot growth dynamics by decreasing substrate moisture content in the early phase of plant establishment. However, decrease in pot’s depth did not influence rooting growth, establishment and dry matter as influenced by the shortage of substrate moisture contents.

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