Wheat Lodging and Yield in Response to Some Field Management Practices

By

MOHAMMAD FADEL TOLBA ZENHOM

B. Sc. Agric. (Agronomy), Fac. of Agric., Moshtohor, Benha Univ., 2006.
M.SC. Agronomy Sci., Benha University, 2013

A THESIS

Submitted in Partial Fulfillment of
the Requirements for the degree of

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IN

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(AGRONOMY)

Department of Agronomy
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ABSTRACT

There is a general belief that all cultivated wheat varieties in Egypt have strong stem lodging resistance because they follow semi-dwarf group. However, some of these varieties suffering from another type of lodging known as root lodging. Four crop management factors including cultivar, plant growth retardant (PGR), mineral N rates and plant density were used in two separated field experiments at Moshtohor, Banha, Egypt, during 2015/2016 and 2016/2017, to investigate how far these factors could modify plant characters, lodging behavior and yield. In the first experiment, 5-cultivars including Misr2, Gemmeza11, Shandaweel1, Giza171 and Sids12 were planted at density of 450 kernels m^{-2}, and sprayed by paclobutrazole at 0, 100 and 200 ppm in two equal portions, at the beginning of tillering and stem elongation stages. In the second experiment, Giza171 was planted at 250, 350 and 450 kernels m^{-2} and fertilized by 5-mineral N rates including 0, 25, 50, 75 and 100 kg fad^{-1}.

Root lodged plots occurred during anthesis stages in both experiments. Combined analysis of Exp1, showed that both of Giza171 and Sids12 scored maximum lodging by 64 and 70, respectively, while the others did not lodge at all. Lodged cultivars yielded averagely 9.7 % less than the total average of the resistant cultivars due to the negative effects of lodging, in particular, lighter kernels weight. All root characters were negatively correlated with lodging score (r, ranged from -0.48 to -0.73, $P<0.01$). Results of simple and multiple linear regressions analysis showed that taller roots which extend vertically in the soil and/or more tillers per plant, were the key variables when deciding important characters for selecting for cultivars with lodging resistance.

PGR treatments induced many positive modifications in shoot and root characters, but these modifications were still not sufficient to improve lodging resistant. These positive alternations by PGR for plant characters did not include both of root length and depth and matched with the unchanged in lodging behavior either. Therefore, using the PGR in this study had leaded us successfully to realize the important role of each of root length and depth for lodging resistance. PGR applications slightly improved grain yield by insignificant 5.6 %, but improved straw yield significantly, whereas harvest index was kept unchanged. The only interaction of cultivar × PGR levels was observed only for the structural root diameter.

Combined analysis of Exp2, showed that the effects of plant density on crop structure which related to lodging susceptibility, was much greater and dominant when compared with the main effect of N rate. Lodging scores were severely affected by increasing plant density per unit area, while it did not differ by N rates. Lodged plants at density of whether 350 or 450 kernels m^{-2} were associated with grain and straw yields losses by 11.5 and 8.7 %, respectively than unlodged plants at 250 kernels m^{-2}. Unlodged plants were supplemented always by better root characters than lodged plants.

Most of root and shoot characters were responded positively by increasing N rates. Spikes m^{-2} responsed exponentially by increasing N rates, while kernels $spike^{-1}$, thousand kernel weight and harvest index did not. Giza171 yielded higher grain and straw yields at 75 kg N fad^{-1}. The interactions between these two factors were insignificant for all traits of study.

For reducing lodging especially in areas that have adversely weather conditions we recommended either Misr2 or Gemmeza11 or Shandaweel1 for these areas. There is no need to use PGR for either managing root lodging or increase grain yield. Concerning the future wheat breeding programs for root-lodging resistance and higher yielding, we suggested introducing taller and deeper roots with more tillers per plant. We recommended seeding rate of 45 kg fad^{-1} (250 kernel m^{-2}) and 75 kg N fad^{-1} to achieve higher yields of Giza171 and prevent root lodging.

INTRODUCTION

Spring wheat (*Triticum aestivum* L.) is considered to be the first strategic crop in Egypt. The total production of wheat reached at least 9000000 tons annually (FAO, 2016). However, these enormous amounts have not been sufficient for the yearly local consumption, due to the continuous increasing in the people density and various types of wheat's losses during the crop preparing processes such as seeding rates, pests, lodging, harvesting, threshing, storage, transporting, milling, baking processes, in addition to human consumption losses and animal feeding. Yet, there are many official statistics included all these kinds of wheat losses, which may reach totally about 1,729000 ton yearly (Hamada, 2015), but wheat lodging losses were not included. Additional amounts of wheat have been imported annually to recover our local demands that cost above 2.7 billion dollars yearly (FAO, 2013). Consequently, all wheat losses including lodging should be minimizing at the lower levels to reduce the import's quantities and preserve the foreign currency.

Lodging occurs either due to root lodging, failure of the anchorage system of plant, or by buckling/bending at the basal culm internodes. In Egypt, all wheat varieties follow spring semi-dwarf group which in most cases had a highly stem resistance for lodging, due to some culm characteristics such as moderate height (about 100 cm), short basal internodes on main stem, stiffer straw, larger culm diameter wall width and composition.. However, some of these varieties suffer from root lodging which occurs at flowering stage and causes loss in yield. Root lodging is defined as the permanent displacement of plant stems from their vertical position because of wind acting on the shoot and rain or irrigation weakening the soil and reducing anchorage strength.

In Egypt, wind speed increases during flowering stage in February or March, thus wheat plants are expected to flatten during the 4th surface irrigation (anthesis stage) because insufficient anchorage strength to hold the plant up against all forces that induce plant to lean. Delaying irrigation after wind speed decreases to avoid lodging is considered as a common practice by farmers to avoid lodging, but changes in wind speed have extended unpredictably during this period. Moreover, farmers pay special attention either to apply the last irrigation or not because of the intensity wind and certainly will not if there already lodging in the field. However, this practice may be crucial for it can reduce both kernels per spike and kernel weight during grain development and resulting grain yield loss. Yield losses from water stress can be the most critical for wheat at anthesis stage. Several studies reported that the major reductions in grain yield occur when wheat lodged flat at anthesis or early in grain filling stage. Grain yield losses caused by lodging could reach 7-80%. Other negative effects of lodging including reduced grain quality, greater drying costs, slower mechanical harvest, large reductions in bread-making quality and increased susceptibility to pests and diseases.

Since lodging is a complicated phenomenon that is influenced by the interaction between genotype with environmental factors, selection resistance cultivars and following suitable field practices will minimize lodging risk. Differentials among cultivars characteristics for both ariel and underground parts, and the ability to improve their root characters are essential for reducing root lodging. Proper plant height, weight and tillers with favorable high values of root plate spread, root depth, root length, roots number per plant and their diameter or dry weights, could be separately or collectively responsible for lodging resistance.

Other critical management practices for managing root lodging are plant growth retardants (PGR), plant density and nitrogen rates. Application of PGRs is a widely common practice for management lodging which can modify some plant characters such as plant height. PGRs reduce lodging risk by shortening crops, but there is little published evidence that they can strengthen anchorage system. The major types of PGRs that have been used exclusively in cereal production including Cycocel, Ethephon, but Paclobutrazole has been used in only one published research concerning the stem lodging in rice. Although paclobutrazole had found to improve root: shoot ratio in some vegetative crops, but there is no any published researches on its impact on plant characters, in particular, root traits in wheat.

Plant density per unit area is considered a crucial factor for managing root lodging. Root lodging occurred particularly at higher seeding rates. At the current moment, high seed rate of 60 kg fad^{-1} is widely used by farmers for tradition broadcasting method which theoretically equal above 350 plants m^{-2}. Previous work has shown that root lodging risk increases linearly by increasing plant density above 250 plant m^{-2} due to the failure of root anchorage system. At higher plant densities, coronal roots have rotated as its windward edge below the soil surface under flood irrigation conditions. On the other side, yield structure of *Triticum aestivum* L is adjustable across a wide range of plant densities due to the compensation ability of plants. Consequently, relationships between wheat plant density as a number of plants per meter square and lodging and/or grain yield are crucial and very flexible.

Mineral nitrogen fertilization has been essential tool for ensuring maximum wheat yields and quality. Despite advantages of applying nitrogen for wheat crop, it can also affect root lodging indirectly. Higher nitrogen rates could increase shoot: root ratio, which could easily tended plants to lodge. Accordingly, determining appropriate rates of nitrogen to achieve higher yields and making lodging at very low level are very important.

Since there is no realistic assessment of wheat lodging in Egypt, there is a general belief that there is no lodging for our semi-dwarf cultivars and this is true for stem but not for root lodging, therefore, these crop management factors, could greatly illustrate how far the differences in traits among plants could protect it against root lodging. Determination of possible plant characters that are associated with lodging resistance is necessary for future wheat breeding programs. Consequently, recommend suitable strategies for whether reduces lodging risks and achieve economic yield of wheat.

REVIEW OF LITERATURE

In this chapter, we discussed four key crop management factors: plant growth retardants, cultivar, mineral nitrogen rates and plant density. These factors greatly illustrate how far the differences in traits among plants could protect it against root lodging. Consequently, determine suitable strategy for whether reduces lodging risks and achieve economic yield of wheat.

In this chapter, we discussed lodging topics that related to whenever traits within any factor firstly, then we discussed literatures that did not consider lodging. It is important to mention that root and shoot characters were discussed in this chapter, almost at anthesis stage.

I- Effect of plant growth retardants:

Plant hormones are chemicals that regulate plant growth. Hormones determine the formation of flowers, stems, leaves, the shedding of leaves, and the development and ripening of fruit. Plant hormones shape the plant, affecting seed growth, time of flowering, the sex of flowers, senescence of leaves, and fruits. They affect which tissues grow upward and which grow downward, leaf formation and stem growth, fruit development and ripening, plant longevity, and even plant death. They are naturally produced within plants, though very similar chemicals are produced by fungi and bacteria that can also affect plant growth. A large number of related chemical compounds are synthesized in laboratories. They are used to regulate the growth of cultivated plants, weeds, and in vitro-grown plants and plant cells; these manmade compounds are called plant growth regulators.

Plant growth regulators, also known as plant exogenous hormones, are synthetic substances that are similar to natural plant hormones. They are used to regulate the growth of many field crops and are important measures to ensure agricultural production. There are two types of plant regulators, plant growth stimulators and plant growth inhibitors or retardants.

Plant growth retardants (PGR) are used to reduce the shoot length and lodging in cereal plants. This is mainly achieved by reducing cell elongation and decreasing the rate of cell division. The major types of PGRs that have been used in cereal production including inhibitors such as: Cycocel or CCC (chlormequat chloride), Ethephon (2-chloro ethyl phosphonic acid) and trinexapac-ethyl. Paclobutrazole has been used successively for reducing plant height, improving stem thickness, improving root to shoot ratio, increase in epicutilar wax and enhancement in chloroplast synthesis **(Berova and Zlatev, 2000; Sinniah *et al*., 2012)**.

The continued improvement in yields in some countries has been significantly aided by the use of PGRs that further reduce crop height making cereals even more resistant to lodging. In France, Germany and the UK, which have among the highest cereal yields in the world, PGRS have been applied to more than 70 % of wheat area **(Berry *et al*., 2004)**. PGRs use may be restricted if maximum residue limits of these substance detected in grains of treated crops **(Juhler and Vahl, 1999)**. PGRs will not be hazardous to human health if they are used in accordance with good agricultural practice.

A) Lodging score:

Pinthus (1973) defined root lodging as the perdominant type of lodging occurring in cereals as a result of reduced plant anchorage when soil wetted by rain or irrigation. **Easson *et al*. (1995) and Pinera-Chavez *et al*. (2016)** reported that lodging risk increases when the soil surface is wet, typically when the first 50 mm of soil is at field capacity. This can be attributed to the movement of plant crown in a saturated soil surface after flood irrigation in irrigated environments **(Fischer and Stapper, 1987)** or after precipitation in rainfed environments **(Crook and Ennos, 1994)**. It is well known that water supply in most spring wheat worldwide is given by flood irrigation in flat beds, it therefore seems sensible to consider the root lodging risk when soil surface is moist **(Pinera-Chavez *et al*., 2016).** Farmers may cancel the last irrigation or delay it (normally at grain filling) depended on the wind speed to reduce lodging or to avoid moistening the lodged areas that already occurred. This is a very crucial decision because avoiding the last irrigation results in grain yield losses **(Hobbs *et al*., 1998**; **Pinera-Chavez *et al*., 2016).**

Application of plant growth inhibitors is a widely common practice for management lodging in many countries. Earlier in 1968, **Humpfries** has mentioned that the application of PGRs to the crop lowers the lodging risk. On a silt loam soil, **(Knapp *et al*., 1987)** planted wheat in rows at plant density of average 458 kernels m^{-2} and treated it by CCC with approximately 0.71 kg a.i. fad^{-1} at the early stem elongation stage (GS 31) or via Ethephon with approximately 0.12 kg a.i. fad^{-1} at early booting stage (GS 41). Lodging score has been reduced significantly by both PGRs and these reductions were 43 and 57 % for CCC and Ethephon, respecively when compared with untreated plants. In addition, Ethephon and CCC applications were reported to be useful in reducing plant height and subsequently reducing lodging in wheat **(Crook and Ennos, 1995)**. In addition, their data indicate that PGR applications could reduce root lodging by averaged 15 % when compared to untreated plants across two cultivars and nitrogen rates. They concluded that PGRs have an indirect benefit on root lodging resistance by shortened plant height so that the overturning moments generated by the weight of the shoot were less.

Resistance to root lodging mechanism depended both upon the self-weight moment of the stems (generated by stem height and weight) which is transmitted into the roots and on the ability of the root system to resist these overturning moments as described by **Crook and Ennos (1993, 1994)**. These findings by them have been indicated that plants resistant to lodging have strong anchorage that could resist self-weight moments generated by the stems whilst plants susceptible to lodging, either produced weak root system that conferred poor anchorage or generated greater self-weight moments because their stems were tall. In other words, Wind-induced forces on a plant will be transmitted into the ground and may eventually cause the stem to lean permanently. Once a plant is leaning, the weight of the aerial parts of the stem will also help to pull the plant over **(Crook and Ennos, 1994)**. Overturning moments would be maximized by tall and/or heavy plants; strong forces by wind and/or rain; weak soil-root conditions thus lodging happening would be strongly expected. It should be mention that leverage is a term which describe previous forces collectivelly that induce plant to lean.

Berry *et al*. (2004) reported that the extent to which PGRs reduce lodging is determined by the ability of the chemicals to alter the morphology of the plant in a way that reduces lodging risk and the amount of PGR that can reduce lodging. He added that the reduction in the area lodged could reach up to 70%. Minimizing root lodging risk by over 50 % via Baytan (triadimenol, growth inhibitor), has been found by **Griffin (1998)**. He reported also that a mixture application of CCC and Terpal (mepiquat chloride and 2-chloro ethyl phosphonic acid) has been reduced lodging risk.

Similarly, **Berry *et al.* (2000)** found that PGRs application was reduced lodging susceptibility.

In Mexico, on a sandy clay soil, **Tripathi *et al.* (2003)** planted wheat in rows at plant density of 300 kernels m^{-2} and sprayed plants by Ethephon (approximately 200 g a.i. fad^{-1}) at the end of stem elongation stage (GS 38). They concluded that Ethephon application prevented lodging which was associated with the reduction in plant height. Moreover, these substances also improve the stiffness of straw, which was more related with stem-lodging resistance, rather than root lodging resistance. **Tripathi *et al.* (2004)** planted wheat in rows at plant density of 300 kernels m^{-2} and sprayed plants by Ethephon (approximately 200 g fad^{-1}) at the end of stem elongation stage (GS 38), and their data indicated that Ethephon application controlled lodging across 16 genotypes (9-susceptible; 7-lodging resist) by reducing plant height. Furthermore, Ethephon application has been reduced lodging score by at least 43.4 % when compared with untreated plants. **Ramburan and Greenfield (2007)** planted wheat in rows at plant density of 400 kernels m^{-2} and sprayed plants by Ethephon during stem elongation stage. Their data showed similar trend that lodging score of treated plants was significantly lower than untreated plants by 28 and 50 % for the first and second locations, respectively. In Malaysia, **Sinniah *et al.* (2012)** sown rice in a greenhouse with seeding rate equivalent to 25 kg fad^{-1} and sprayed plants by Paclobutrazol at 0, 50, 100 and 200 ppm during panicle initiation. Lodging resistance of treated plants at either 50 or 100 or 200 was found to be significantly higher than untreated plants by averaged 27.3 % due to the reduction in culm length.

B) Root characters:

Several rooting characters have been associated with root-soil anchorage strength including the spread of the root plate, roots number, root dry weight, root length, rooting depth and root thickness. The spread of the root plate has been linked most strongly with anchorage strength rather than other rooting characters as well documented by many investigations. PGRs reduce lodging risk by shortening crops, but there is little published evidence that they can strengthen anchorage system **(Berry *et al*., 2004).** Therefore, they have been suggested more studies to investigate the effects of a wider range of PGRs, application rates and timings on the relevant plant characters before strong conclusions can be drawn about their effect on strengthening root anchorage system.

1. Root plate spread:

Crook and Ennos (1995) showed that growth inhibitors mixture of CCC followed by mepiquat chloride applied to winter wheat at the beginning of its stem extension did not affect the spread of the root plate across two cultivars, which were differed in lodging resistance. Use of a Baytan seed treatment reduced root lodging risk by causing a significant enlargement in the spread of the root plate, which was widen by 17.4 % **(Griffin, 1998)**. In UK, on a silt clay loam, **Berry *et al*. (2000)** found that PGR treatments did not affect the spread of the root plate.

2. Number of roots per plant:

Bragg *et al*. (1984) showed that CCC application before the onset of stem elongation increased the winter wheat roots during stem elongation. By inspecting data from **Crook and Ennos (1995)**, number of roots per plant of treated plants by CCC followed by mepiquat chloride, was significantly ($P<0.001$) increased by 34.4 % when compared with untreated plants (averaged 6.3 root plant^{-1}) across lodging resistant and susceptible varieties. The seed treatment Baytan can increase root number per plant by 25 % as data shows from **(Montfort *et al*., 1996)**.

3. Structural rooting depth:

The seed treatment Baytan can increase rooting depth by retarding growth of the subcrown internode **(Montfort *et al*., 1996)**. Use of a Baytan seed treatment had reduced root lodging risk by causing significant deeper roots which was deepened by 25.3 % **(Griffin, 1998)**. He suggested that Baytan may reduce lodging, not only by causing plants to set deeper crowns which improves anchorage strength, but also by encouraging earlier crown root growth, resulting in larger spread of the root plate. The beneficial effects of Baytan on reducing lodging probably arise through consequent increases in structural rooting depth. **Berry *et al*. (2000)** found that growth inhibitors mixture of CCC followed by mepiquat chloride applied to winter wheat at the beginning of its stem extension did not affect structural rooting depth.

4. Structural root length:

Bragg *et al*. (1984) found that application of CCC at seedling stage, slightly enhanced root length in winter barely. **Woodward and Marshall (1987)** found that root length of barley was reduced by Ethephon application. **Griffin (1998)** showed that root length at milk stage of winter wheat was doubled when CCC and Terpal were applied than untreated plants. **Rajala *et al*. (2002)** showed that the length of wheat roots was not affected significantly by three PGRs which were applied during the seedling stage.

5. Structural root diameter:

No scientific articles were published before concerning the effect of PGR treatments on structural root diameter directly.

6. Root dry weight per plant:

Humpfries (1968) observed greater root weight in plants which dwarfed by application of PGR. **Bragg *et al.* (1984)** showed that CCC application before the onset of stem elongation increased the mass of winter barley roots. **Naylor *et al.* (1986)** found a reduced shoot:root ratio after chlormequat was applied to barley at early stages of growth (GS 14). However, it is not known whether the shoot:root ratio was decreased by an increase in root mass or a reduction in shoot growth. In contrast with above results, **Woodward and Marshall (1987)** observed that Ethephon alone, and with mepiquat chloride, inhibited the root growth of barley. Again, CCC increased the root dry matter of winter wheat by 8% as found by **Blouet *et al.*, 1991**. Converesly, data of **Rajala and Peltonen-Sainio (2001)** has been shown that root dry weight of spring wheat was not affected by Ethephon or trinexapac-ethyl (growth inhibitors) while it decreased by 17 % via CCC application when compared with control. Root dry weight means were ranged from 236 to 284 mg in their trail.

C) Growth:

1. Plant height:

Application of plant growth inhibitors is a widely common practice for management lodging which can modify some plant characters such as plant height. Leverage or lodging risk may be reduced by growing short plants, either by selecting short varieties **(Pinthus, 1973; Berry *et al*., 2000)** or applying plant growth inhibitors **(Humpfries, 1968; Crook and Ennos, 1995; Berry *et al*., 2000)**. Data of **Knapp *et al*. 1987)** indicated that the total culm length was reduced significantly (P<0.01) by plant growth regulators and these reductions were 8.2 and 10.7 % for CCC and Ethephon, respecively when compared to untreated plants, therefore lodging score were significantly reduced in both seasons. In Pakistan, **Alam *et al*. (2002)** sprayed wheat plants by Ethephon at 10, 20 and 30 ppm during stem elongation stage.Data showed that the differences in plant height were not exceeding three centimeters between treated and untreated plants, and the shortest plants were obtained by Ethephon appilcation at 20 ppm. In the absence of lodging, **Humphries *et al*. (1965)** treated spring wheat plants by CCC at mid-seedling stage and found that plant height was significantly reduced by averaged 35 %. Under same conditions, **(Rajala and Peltonen-Sainio, 2002)** treated spring wheat plants by CCC or Ethephon at mid-seedling stage and found that plant height was significantly reduced by averaged 6 %. Furthermore, **Lowe and Carter (1972)** and **Rajala and Peltonen-Sainio (2002)** treated spring wheat plants by CCC at the beginning of stem elongation stage and found that plant height was significantly reduced in the range of 29 %.

Data obtained by **Tripathi *et al*. (2003)** showed that plant height of Ethephon-treated plants was significantly shorter than untreated plants by 12.6 and 7.5 % for the first and second seasons, respectively and these reductions significantly reduced wheat lodging. Data of **Tripathi *et al*. (2004)**indicated that plant height of Ethephon-treated plants was significantly shorter than untreated plants in two seasons by averaged 9.8 %, and these reductions significantly reduced wheat lodging. **Ramburan and Greenfield (2007)** data showed that plant height of Ethephon-treated plants was significantly shorter than untreated plants by 3.8 and 9.1 % for the first and second locations, respectively and these reductions were significantly reducing lodging score in the two locations. In Iran, **Shekoofa and Emam (2008)** planted winter wheat in rows at plant density of 250 kernels m^{-2} and sprayed plants by CCC with approximately 0.92 kg a.i. fad^{-1} at mid-tillering stage (GS 25) or Ethephon with approximately 0.12 kg fad^{-1} at the end of stem elongation stage (GS 39). Data imply that plant height was reduced significantly by both of growth inhibitors by average 3.1 % when compared with untreated plants. Besides these results, **Sinniah *et al.* (2012)** mentioned that treated plants by Paclobutrazole at 200 ppm induced severe retardation by 20% for culm length when compared with untreated plants.

In a field experiment, **Crook and Ennos (1995)** sprayed 2 winter wheat cultivars by CCC followed by Terpal during stem elongation stage to manage lodging, at nitrogen and seeding rates of approximately 67 kg fad^{-1} and 400 kernels m^{-2}, respectively, in UK. By inspecting their data, plant height of treated plants was significantly ($P<0.001$) reduced by 12 % when compared with untreated plants**.** **Flintham *et al.* (1997)** also prevented lodging by plant growth regulators and considered plant heights of 70 cm as an optimum height for reduce lodging risk and maintaining economic yield. **Griffin (1998)** found that a mixture application of Cycocel and Terpal reduced lodging risk by shortenening plant height by 7 – 22 %. **Berry *et al.* (2000)** strongly suggested that to achieve lodging-proof wheat, shoot height should be kept as short as possible for the future genotypes and applied growth inhibitors such as Cycocel followed by Terpal had reduced plant height effectively in their study. **Berry *et al.* (2004)** has defined lodging proofness as : "the structure that can withstand the strongest wind likely to occur over a cereal crop once every generation". He also mentioned that growth regulating chemicals have been shown to reduce plant height by 0 to 40 % depending on the type of active ingredient, the cereal species, the stage of development and the environmental conditions. Application of plant growth inhibitors such either Ethephon or Cycocel or Terpal for winter/spring wheat was associated with reduced plant height in the range of 10-15 % **(Berry *et al*., 2004)** and improved lodging resistance.

2. Number of tillers:

More tillers per square meter are mostly associated with growth inhibitors application **(Humpfries, 1968**). A mixture application of CCC and Terpal or CCC alone, significantly decreased number of tillers per plant by averaged 10.3 % as found from the results of **Griffin (1998)**. On the other hand, data of **Rajala and Peltonen-Sainio (2001)** showed that number of tillers per wheat was significantly increased by 16.5 % when plants were treated by either Ethephon or trinexapac-ethyl application. However, CCC application did not change tillers number when compared with the control. Again, data indicated that sprayed wheat plants by Ethephon at both of 20 and 30 ppm increased the number of tillers per square meter by 7.1 and 2.3 % when compared with untreated plants, as found in a research by **Alam *et al*. (2002)**. Furthermore, the number of tillers per square meter of Ethephon-treated plants was significantly more than untreated plants by 4.3 and 12.5 % for the first and second seasons, respectively **(Tripathi *et al*., 2003)**. **Berry *et al*. (2004)** reported that more tillers are mostly associated with PGR treatments. Results of **Shekoofa and Emam (2008**) showed also that both of CCC and Ethephon increased number of tillers per square meter significantly by at least 6.3 % when compared with untreated plants.

3. Shoot fresh weight per plant:

By inferring data of (**Crook and Ennos, 1995)**, PGR application significantly reduced stem and spike fresh weights at grain filling by 11% and 10.5%, respectively when compared with untreated plants across two winter wheat cultivars.

4. Shoot dry weight per plant:

Results of **Rajala and Peltonen-Sainio (2001)** showed that shoot dry weight of wheat was significantly decreased by averaged 16.8 % when plants were treated by either Ethephon or trinexapac-ethyl or CCC when compared with control. Results of **Tripathi *et al*. (2004)** revealed that dry weight of plants was not affected by Ethephon application in the first season, but in the second season treated plants were significantly heavier than untreated by 3.5 %. Data of **Shekoofa and Emam (2008)** indicated also that plant dry weight was increased significantly by both of CCC and Ethephon by average 22.7 % when compared to untreated plants and these increases were matched with increasing in tillering rate.

D) Yield and yield components:

1- Number of spikes per square meter:

Data of **Tripathi *et al*. (2004)** showed that treated wheat plants by Ethephon had no significance impact on the number of spikes per square meter in two seasons, but it seemed that treated plants was higher by 20 spikes m^2 than untreated plants in both seasons. Moreover, Lodging was occurred late, 25 to 30 days after anthesis, therefore it seemed that the number of spikes per square meter was not affected by lodging. Data from

Ramburan and Greenfield, (2007) indicated that treated plants by Ethephon produced more spikes per square meter than untreated plants by 6.8 % in the first location while the number of spikes did not differ for the second location. However, data of **Shekoofa and Emam, 2008** indicated that number of spikes per square meter was increased significantly by both of CCC and Ethephon by average 6.3 % when compared with untreated plants. In 2012, **Sinniah *et al*.** 's data indicated that treated rice plants by Paclobutrazole at either 50 or 100 or 200 ppm had no significance impact on the number of panicles per unit area.

A set of experiments were conducted to study the impact of PGRs on number of spikes but in the absence of lodging conditions. For instance, both of **(Humphries *et al*., 1965; Humphries and Bond, 1969)** treated spring wheat plants by CCC at mid-seedling stage and they did found that the number of spikes per square meter was significantly increased. However, **Rajala and Peltonen-Sainio (2002)** treated spring wheat plants by CCC or ethephon at mid-seedling stage and found no differences in spikes number per square meter by both regulators. Same results by **Lowe and Carter (1972)** and **Rajala and Peltonen-Sainio (2002)** as they treated spring wheat plants by CCC at the beginning of stem elongation stage and found no differences in spikes number per square meter. However, **Berry *et al*. (2004)** reported that PGRs in the absence of lodging showed increases in wheat grain yield which were associated mainly with an increase in spikes number per square meter. Large spikes number is most frequently associated with growth inhibitors application as mentioned by them.

2- Number of kernels per spike:

Berry *et al*. (2004) stated that the grain yield reductions could be as much as 50 % and were caused by decreases in the number of kernels per spike and kernel weight that outweighed increases in spike number. On the contrary of these results, data indicated from **Ramburan and Greenfield (2007)** that number of kernels per spike did not affect significantly by Ethephon application for the two locations, while it was increased by averaged 4.8 % via CCC application. Also, data of **Shekoofa and Emam (2008)** showed that treated plants by CCC or Ethephon had no significance impact on the number of kernels per spike. By inspecting data from **Sinniah *et al*. (2012)**, treated rice plants by Paclobutrazole at either 50 or 100 or 200 ppm had the same effect on the number of grains per panicle but these dosages increased grains panicle^{-1} significantly by averaged 4.7 % when compared with untreated plants.

A set of trials were concerning the PGR 's effect on the number of kernels per spike but in the absence of lodging conditions. For instance, **Humphries *et al*. (1965)** treated plants by CCC at mid-seedling stage and found that the number of kernels per spike was not affected. However, **Humphries and Bond (1969)** found that treated spring wheat plants by CCC at mid-seedling stage increased the number of kernels per spike. In contrast with them, **(Rajala and Peltonen-Sainio, 2002)** treated spring wheat plants by CCC or ethephon at mid-seedling stage and found no differences in kernels number per spike by both regulators. The same findings were obtained by (**Lowe and Carter, 1972**; **Rajala and Peltonen-Sainio, 2002)** as they treated wheat plants by CCC at the beginning of stem elongation stage and found no differences in kernels number per spike. However, results of

Tripathi *et al.* (2004) showed that treated wheat plants by Ethephon application sharply decreased the number of kernels per spike in both seasons by averaged 12.5 % when compared with untreated plants across 16 genotypes that were varid in lodging behavior. In addition, lodging occurred late, 25 to 30 days after anthesis, therefore this reduction in kernels spike^{-1} was primarily associated with Ethephon application not to lodging. They also metioned that Ethephon acted more to reduce kernel number rather than its weight.

3- Thousand kernel weight:

Data from **Griffin (1998)** showed that a mixture application of Cycocel and Terpal or Cycocel alone had significantly reduced the thousand kernel weight in the range of 3.7 %. **Berry *et al.* (2004)** reported that the grain yield reductions were caused by decrease in the kernels weight when growth inhibitors were applied due to the increases in spikes number. On the other side, data of **Ramburan and Greenfield (2007)** indicated that kernel weight was not affected significantly by CCC application for the two locations. However, it was decreased significantly by averaged 5 % via Ethephon application. In contrast with previous findings, data of **(Shekoofa and Emam, 2008)** showed that thousand kernel weight was increased significantly by both of CCC and Ethephon by average 2 % when compared with untreated plants. They explained these increases in grain weight due to the higher rates of photosynthesis and photo-assimilate partitioning to the grains, or longer periods of grain filling or both of them when PGRs applied. Similarly, data of **Sinniah *et al.* (2012)** indicated that treated rice plants by Paclobutrazole at 100 ppm had increased grain weight significantly when compared to those which are produced at whether 200 ppm or untreated plants.

A set of experiments were conducted to study the impact of PGRs kernels weight but in the absence of lodging conditions. For example, **Humphries *et al*., 1965** treated spring wheat plants by CCC at mid-seedling stage and found that thousand kernel weights were not affected. However, **Humphries and Bond (1969)** found that treated wheat plants by CCC at mid-seedling stage had decreased kernels weight. **Rajala and Peltonen-Sainio (2002)** treated wheat plants by CCC or ethephon at mid-seedling stage and found significant reduction in kernels weight by CCC only. **Lowe and Carter (1972)** and **Rajala and Peltonen-Sainio (2002)** treated wheat plants by CCC at the beginning of stem elongation stage and the first found no differences in kernels weight whilst the second observed significant redcution in kernels weight. Similar findings which obtained by **(Humphries *et al*., 1965; Lowe and Carter, 1972)** were observed for **Tripathi *et al*. (2004)** as their data showed that the kernel weight was not affected significantly by Ethephon application with averaged 41 g. In addition, lodging was occurred late, 3-weeks before harvest, therefore it seemed that lodging did not change kernel weight of treated or untreated plants.

4- Grain yield per faddan:

Data of **Griffin (1998)** showed that a mixture application of Cycocel and Terpal or Cycocel alone did not affect grain yield. Results obtained by **Knapp *et al*. (1987)** showed that treated plants by CCC had increased grain yield by only 5.6 % than untreated plants, while treated plants by Ethephon produced grain yield as similar as untreated plants across nitrogen rates, PGRs and years. Although, PGRs application was useful for decreasing lodging in their trial but the limitation of effectivness of these substances for increasing grain yield could be propably due to the lodging time which was very late at the end of milk stage of grains (GS 77). **Berry *et al*. (2000)** mentioned that plant growth inhibitors had lack effect on grain yield due to their limited effect on redistribution of biomass during grain filling. Data from **Alam *et al*. (2002)** indicated that sprayed wheat plants by Ethephon at 20 ppm had increased grain yield by 6.7 % more than untreated plants while at either 10 or 30 ppm the grain yield was decreased by 7.3 and 10.3 %, respectively when compared with untreated plants. Data of **Tripathi *et al*. (2004)** showed that Ethephon application controlled lodging but decreased grain yield in the first and second seasons by 13 and 4.3 %, respectively when compared with untreated plants. However, lodging occurred late, 25 to 30 days after anthesis, therefore the yield reduction was primarily associated with a significant reduction in number of kernels per spike not to lodging.

Ramburan and Greenfield (2007) observed that grain yield of untreated and treated plants by PGRs were similar for the two locations. Although, PGRs application was useful for decreasing lodging in their trial but the limitation of effectivness of these substances for increasing grain yield could be propably due to the lodging time which was very late. Results from **Shekoofa and Emam (2008)** showed that grain yield was increased significantly by both of CCC and Ethephon by averaged 15.9 % when compared with untreated plants and those researchers explained these increases in yield by the alternation of dry matter partitioning into spikes when plant height had reduced by growth inhibitors. In Canada, on silty caly loam soil, **(Brinkman, 2012)** sprayed winter wheat by CCC (approximately 0.48 kg fad^{-1}) at the end of tillering stage (GS 29), and their data showed that CCC application did not affect grain yield for six sites and three seasons.

However, **Sinniah *et al.* (2012)** mentioned that foliar application of Paclobutrazol increased rice grain yield directly by 8% and indirectly through decreases in losses of up to 20% due to lodging. Their data also showed that grain yield of treated rice by Paclobutrazole at 100 ppm had exceeded those which were achieved at 200 ppm by 6 %.

In the absence of lodging, **Humphries *et al.* (1965)** treated wheat plants by CCC at mid-seedling stage and found that grain yield was not affected. However, **Humphries and Bond (1969)** found that treated wheat plants by CCC at mid-seedling stage had increased grain yield in the range of 15 %. In the absence of lodging, **Rajala and Peltonen-Sainio (2002)** treated wheat plants by CCC or ethephon at mid-seedling stage and found no differences in grain yields by both regulators. Under the same conditions, **Lowe and Carter (1972)** and **Rajala and Peltonen-Sainio (2002)** treated spring wheat plants by CCC at the beginning of stem elongation stage and the first found no differences in grain yield whilst the second observed significant redcution in grain yield by 8 %. **Berry *et al.* (2004)** reported that plant growth inhibitors in the absence of lodging showed inconsistent results on wheat grain yield. It could either increases yield by zero to less than 15 % or reducing the grain yield as much as 50%. Increases in grain yield are often associated with increases in tillers and/or spikes number per unit area. Increasing the spikes number will only increase grain yield when the source of assimilates is not limiting. If it is limiting then either fewer grains will be set or/and the grains will be lighter and the effect of greater spikes number will be countered **(Berry *et al.*, 2004)**. In addition, the yield reductions that caused by decreases in the number of grains per spikes could attributed to both the promotion of late-appearing shoots with relatively few grains, and the abortion of distal florets on the main stems and early appearing tillers.

5- Straw yield per faddan:

By inspecting data of **Griffin (1998)**, a mixture application of Cycocel and Terpal or Cycocel alone, significantly reduced straw yield by averaged 4.3 %. Data from **Alam *et al*. (2002)** indicated that sprayed wheat plants by Ethephon at either 10 or 20 ppm had increased straw yield by 6 % more than untreated plants while at 30 ppm the straw yield was as similar as untreated plants. By inspecting data of **(Tripathi *et al*., 2004)**, sprayed wheat plants by Ethephon had increased straw yield in the first and second seasons by 2.8 and 7.5 %, respectively when compared with untreated plants across 16 genotypes that were varid in lodging behavior. In contrary of previous results, data of **Shekoofa and Emam (2008)** showed that treated plants by CCC or Ethephon had no significant impact on the straw yield.

6- Harvest index:

By inspecting data of **Griffin (1998)**, a mixture application of Cycocel and Terpal or Cycocel alone, significantly increased harvest index by averaged 2.6 %. Data of **Alam *et al*. (2002)** indicated that sprayed wheat plants by Ethephon at either 10 or 30 ppm had decreased harvest index by 5.2 and 6.7 %, respectively when compared with untreated plants, while at 20 ppm the harvest index was as similar as untreated plants. Similarly, **Tripathi *et al*. (2004)** showed that Ethephon application controlled lodging but decreased harevest index in the first and second seasons by 9.5 and 9.1 %, respectively when compared with untreated plants. It seemed that this reduction in harevest index was primarily associated with the reduction in grain yield that caused by Ethephon application not to late lodging which was occurred within three weeks until harvest. Nevertheless, data of **Shekoofa**

and Emam (2008) showed that CCC increased harvest index significantly by 13.8 % when compared with untreated plants.

II- Effect of cultivar:

Great strides were made during the 1960s and 1970s to reduce lodging risk by the introduction of semi-dwarf varieties. The yield of these varieties was greater than the traditional varieties for two reasons: reduced stem growth rates during the development of the ear resulted in more fertile florets and more grains per square meter; they could respond to greater amounts of fertilizers because they were less susceptible to lodging. Egyptian experts reported that all our cultivated wheat varieties are followed the semi dwarf group. However, lodging is obvious in many cultivated areas of these varieties in Egypt.

A) Lodging score:

Data of **Knapp *et al*. (1987)** indicated that wheat' s lodging score was differed significantly between Auburn and Arthur71 cultivars, where the last one behavied susceptible for lodging by 82 % more than the first one. In 1990, **Stapper and Fischer** published results of 6 experiments where they tested 4 spring wheat genotypes in the first experiment using 170 plants m^{-2} and their data showed that lodging score was significantly affected by genotypes and ranged from 26 to 46. In addition, they mentioned crops had started lodging at early to late grain-filling stages in their six experiments. In the second experiment, they tested 20-spring wheat genotypes using 200 plants m^{-2} and their data indicated that lodging score was significantly affected by genotypes, which ranged from average 14 to 89. In the third experiment, they tested two-spring wheat genotypes using 130 plants m^{-2} and their data showed that lodging score was significantly affected by genotypes, which ranged from average 53 to 87. The fifth experiment, they tested 16 wheat genotypes using 200 plants m^{-2} and their data showed that lodging score was significantly affected by genotypes and ten of them recorded 0 scores, while the maximum had reached 50.

Results of **Easson *et al*. (1993)** showed that four winter wheat cultivars were established by actual plant density of 392 plant m^{-2} with approximately 75 kg N fad^{-1}, and these cultivars were differed in root lodging severity, where the lodging percentages at anthesis for Longbow, Norman, Hornet and Apollo were 64, 62, 43 and 23 %, respectively. **Crook and Ennos (1994)** studied the effect of root and shoot characteristics on the lodging resistance of four winter wheat cultivars at plant density of 400 kernels m^{-2} on a sandy loam soil, in UK. They found large differences between cultivars in root lodging behavior at grain filling when the soil was wet where lodging percentage was ranged from zero to 100 %. They found that Widgeon had most susceptible, followed by Galahad, Riband and Hereward which, alone, did not lodge at all. They reported that lodging resistance by cultivar was associated with shorter and lighter stems (and hence on the force applied to the plants by wind and gravity) and with high values of the anchorage strength of the root system (and hence on the force resisting lodging). They added that root failure tends to occur late in development, during grain filling**.** Form their data, Galahad was more susceptible to lodge than the resistant Herewad by 41.7 %. **Crook and Ennos (1995)** evaluated two winter wheat cultivars in field trail for root lodging at nitrogen and seeding rates of 67 kg fad^{-1} and 400 kernels m^{-2}, respectively, in

UK. They found significant ($P<0.001$) impact of cultivar on anchorage strength ($P<0.001$) or root-lodging behavior, where Hereward and Galahad were the resistant and susceptible varieties, respectively. **Griffin (1998)** stated that lodging susceptibility significantly differed between seven cultivars of winter. **Spink *et al*. (2003)** noticed that anchorage strength or lodging susceptibility significantly differed between varieties.

Tripathi *et al*. (2003) tested 12 spring semi-dwarf genotypes of wheat using 300 viable kernel m^{-2} and their data showed that lodging score was significantly affected by genotypes and ranged from average 0 to 81. It is be worth to mention that most of their tested genotypes (PASTOR, PAVON, Oasis, Baviacora, Seri82) are from the CIMMYT and considered as parents of our studied cultivars such as Misr2, Gemmeza11 and Shandaweel1. **Tripathi *et al*. (2004)** evaluated 16 spring semi-dwarf genotypes of wheat using 300 viable kernels m^{-2} and their data indicated that lodging score was affected significantly by genotypes and ranged from average 0 to 83. They found that some of higher lodging genotypes could be relate to its higher biomass and grain yields per square meter. **Tripathi *et al*. (2005)** tested 16 spring semi-dwarf genotypes of wheat using 300 viable kernels m^{-2} and their data pointed that lodging score was significantly ($P<0.01$) affected by genotypes and ranged from average 0 to 82. Data of **Ramburan and Greenfield (2007)** showed that the wheat lodging score was differed significantly between Olifants, SST876 and Kariega cultivars where the last one behavied susceptible for lodging by average 77 % more than the other lodging-resist varieties. **Brinkman (2012)** found that lodging was significantly affected by six varieties and ranged from 0 to 92.

B) Root characters:

1- Root plate spread:

In UK, on a sandy loam soil, **Crook and Ennos (1993)** examined four cultivars of winter wheat that were differed in lodging behavior at plant density of 400 kernels m^{-2}. By inferring their data, the spread of the root plate was averaged 26.3 mm for either lodging resistant Hereward or susceptible Galahad. In 1994, **Crook and Ennos**' data indicated that the spread of the root plate of resistant Hereward was less than 2 out of 3 susceptible cultivars by averaged 9.3 % while was similar as to the last cultivar. **Crook and Ennos (1995)** examined two cultivars of winter wheat which were differed in lodging behavior at plant density of 400 kernels m^{-2}, and their data showed the spread of the root plate was similar for either lodging resistant Hereward or susceptible Galahad.

Griffin (1998) found that wider spread of the root plate was 40.5 mm at Beaver, which was wider than other susceptible cultivars in the range of 38.4 %. **Berry *et al*. (2000)** observed that the wider root plates had effectively reduced the risk to root lodging. They strongly suggested that to achieve lodging-proof wheat, new genotypes should have wider root plate**.** Moreover, from our calculations, their data showed that the root plate spread correlated positively with tillers plant^{-1} which r-values were 0.65 and 0.77 for 1994 and 1995 seasons, respectivley. However, they found that increasing tillers per plant had increased lodging and leads to partially countracted the root plate effect which is considered as one of the most root characters for lodging resistance as we indicated before. **Spink *et al*. (2003)** mentioned that lodging susceptibility differed between varieties and wider roots were responding to lodging resistance. **Berry *et al*. 2007 and Sparkes *et al*. (2008)**

recommended also wider root plates for the future lodging-proof genotypes of wheat**.**

Pinera-Chavez *et al*. (2016) improved lodging model to estimate the lodging-associated traits which are required to enable spring wheat grown with a typical yield of approximately 2520 kg fad^{-1} and plant height of 0.7 m; to achieve lodging-resistance ideotype. They estimated that root plate spread of 51 mm was essential trait for that purpose and increased to 55 mm for wheat with a yield of approximately 4200 kg fad^{-1} and plant height of 1.0 m tall. In addition, results of regression analysis across 26 genotypes and two years, data from **Pinera-Chavez *et al*. (2016)** showed that wider root plate could be predicted well by the increases in root dry weight as R^{2} value was 0.74 at $P < 0.001$. They strongly suggested that breeding for a wider root plate will require greater investment in root biomass.

2- Number of roots per plant:

Griffin (1998) found that maximum number of roots per plant was counted at Beaver (13.5 root plant^{-1}), which was more than other susceptible cultivars in the range of 36.3 %. By inferring data of **Crook and Ennos (1993)**, number of roots per plant that has more than 17mm long, was 8.8 roots for the resistant Hereward and more than the susceptible Galahad by 5.7 %. Data of **Crook and Ennos (1994)** showed that number of roots for the resistant Hereward was more than 2 out of 3 susceptible cultivars by averaged 13 % while was less than the last susceptible one by insignificant 6.3 %. In addition, the number of roots per plant which have more than 17mm long, were 9 roots for the resistant Hereward and more than the susceptible Galahad by 20 %. Results of **Crook and Ennos (1995)** pointed that number of roots per plant was significantly affected by cultivar at $P<0.05$ and the lodging-resistant Hereward had produced 7 roots (> 17mm long) per plant and higher than susceptible Galahad by approximately 19.3%. They also reported that Galahad had weaker anchorage system due to the smaller number of roots plant^{-1} when compared with resistant Hereward. They concluded that stronger root system had depended on the number of roots per plant rather than some other differences in root system. They also found that Hereward variety did not lodge regardless of growth regulators treatments. Thus, this could be indicating strongly the importance of selection the resistance cultivar to reduce lodging risks.

3- Structural rooting depth:

By inferring data from **Griffin (1998)** found that deepest roots was 27.7 mm at Candenza which was deeper than other six cultivars in the range of 45.4 %. **Spink *et al*. (2003)** observed that lodging susceptibility differed between varieties and deeper roots showed response to lodging resistance. **Berry *et al*. (2007)** indicated that the variation in rooting depth between varieties was ranged from 31.7 to 46.9 mm. **Thorup-Kristensen (2009)** reported that the roots of winter and spring wheat penetrated the soil at a similar rate but due to the longer growing period, winter wheat roots were deeper than that of spring wheat by twofold.

4- Structural root length:

Griffin (1998) found that greatest root length was observed at Beaver cultivar. By inspecting data from **Crook and Ennos (1993)**, structural root length for the susceptible Galahad was more than the resistant Hereward by 8.9 %. Data of **Crook and Ennos (1994)** showed that structural root length for the resistant Hereward was less than 2 out of 3 susceptible cultivars by averaged 11 % while was more than the last susceptible one by insignificant

10.4 %. **Berry *et al*. (2007)** indicated that the variation in total root length between varieties was ranged from 56 to 125 mm**.**

5- Structural root diameter:

Spink *et al*. (2003) noticed that lodging susceptibility decreased by stiffer or thicker roots that was response for lodging resistance. **Berry *et al*. (2007)** indicated that the variation in root diameter between varieties was ranged from 41 to 80 mm. **(Berry *et al*., 2007; Pinera-Chavez *et al*., 2016)** mentioned that root biomass had found to be consequences of secondary thickening of the upper parts of roots. There was a significant variation in root diameter or thickening between spring and winter wheat **(Pinera-Chavez *et al*., 2016)**. Spring wheat has thinner roots than winter ones.

6- Root dry weight per plant:

Evans *et al*. (1975) reported generally, that the weight of roots for spring wheat is much less than winter ones due to the shorter period of growth at low temperature compared to winter wheat. This may indicate the poor root system in spring compared with winter wheat. **Kasperbauer and Karlen (1986)** stated that wheat partitioned a greater proportion of the assimilate to the extending shoots and away from the root system and this will lead to the reduction in both root dry weight and root components. Data of **Rajala and Peltonen-Sainio (2001)** showed that root dry weight of spring wheat cultivar was averaged 670 mg. **Berry *et al*. (2007)** indicated that the variation in root biomass was strongly correlated (r = 0.91) with the mean root diameter and did not correlate with the total root length or roots number. Moreover, the significant varietal differences between the spread of the root plate were linearly (r = 0.92) related to the root biomass. **Berry *et al*. (2007)** concluded that there is a large genetic variation for root biomass and they suggested that breeders should develop germ-plasm with extra biomass in the roots to make crops lodging-proof. **(Pinera-Chavez *et al*., 2016)** found strong relationship between root dry weight and anchorage strength or root-lodging resistance in spring wheat. **(Pinera-Chavez *et al*., 2016)** found a positive relationship between root dry weight and the most lodging-associated trait as the spread of the root plate. In addition, they concluded that spring wheat might require a great investment in additional root biomass to widen its root plate than winter wheat.

C) Growth:

1- Plant height:

Data of **Knapp *et al*. (1987)** indicated that plant height of the susceptible variety was higher than lodging-resist variety by 10 %. **Stapper and Fischer (1990)** mentioned that differences in height explained more than 80 % of the variation in lodging scores in the experiment, which included four varieties and sowing dates. They also found a well positive correlation between lodging score and crop height in another experiment (r=0.73; n=48). By inferring data from **Easson *et al*. (1993)**, the least lodged cultivar was shorter than the severe lodged cultivar by 7.7 %, whilst was taller than the other two cultivars by averaged 2 %. **Crook and Ennos (1994)** reported that lodging resistance by cultivar was associated with short stems (and hence on the force applied to the plants by wind and gravity). Their data showed that height of the resistant Hereward was 85 cm and less by 33.6 % than Widgeon which was the higher lodged cultivar in their experiment. They considered that shorter plants was a crucial factor for lodging resistance thus, they recommended shorter stems for the new lodging-proof genotypes of wheat.

Crook *et al*., (1994) examined two cultivars of winter wheat which were differed in lodging behavior at plant density of 400 kernels m^{-2}, in UK. By inferring their data, plant height for the resistant Hereward was similar as to the susceptible Galahad. By inspecting data from **Crook and Ennos (1995)**, plant height of lodging-resist variety was 85 cm and significantly taller than the susceptible Galahad by approximately 5%.

Berry *et al*. (2000) strongly suggested that to achieve lodging-proof wheat, shoot height should be kept as short as possible for the future genotypes. Data of **Tripathi *et al*. (2003)** pointed that plant height affected significantly by 12 semi-dwarf genotypes and the lodging resist-genotypes had taller plants than lodged genotypes by averaged 1.9 %. However, they found insignificant negative correlation between plant height and lodging score thus they countered the conventional believe that taller genotypes tended to lodge more than shorter ones. **White *et al*. (2003)** reported that plant height was not well related to the lodging resistance of winter oats, so it seems possible that varietal differences in root traits are important in cereal species. Results of **Tripathi *et al*. (2004)** indicated that plant height was significantly affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had shorter plants than lodged genotypes by averaged 0.8 %. However, the shortest genotype (73 cm) behaved lodging while the tallest one (100 cm) showed no lodging. **Tripathi *et al*. (2004)** found no significant relationship between plant height and lodging behavior. Therefore, those researchers countered the conventional believe that taller genotypes tended to lodge more than shorter ones. Data of **Tripathi *et al*. (2005)** showed that plant height was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had shorter plants than lodged genotypes by averaged 0.9 %. However, the shortest genotype (75 cm) behaved lodging while the tallest one (104 cm) showed no lodging.

Tripathi *et al.* (2005) again found no significant relationship between plant height and lodging behavior. On the other hand, **Navabi *et al.* (2006)** examined the genetic variation for lodging tolerance in different plant height groups, within a diverse population of wheat genotypes (n = 140), and did found that lodging scores were positively correlated with plant height. They strongly suggested that genetic gain in lodging tolerance can be obtained, to some extent, independent of plant height. **(Berry *et al.*, 2007)** reported that lodging could be managed by shorter plants (0.7 m) which considered as a crucial factor for lodging resistance. Nevertheless, data of **Ramburan and Greenfield (2007)** pointed that plant height of the susceptible variety was between the two lodging-resist varieties and the differences did not exceed 2.4-cm thus it seemed that plant height did not affect lodging in their trail.

In fact, several studies also have been shown the impact of cultivars on wheat height regardless of the lodging behavior. For instance, in Egypt, on a clay soil **Abdallah *et al.* (2013)** evaluated two bread wheat cultivars at seeding rate of 70 kg fad^{-1} and they noticed that plant height of Gemmeza10 was 95 cm and significantly taller than Sakha93. Under the same conditions, **Seleem and Abd-Eldayem (2013)** planted five bread wheat cultivars including Misr1, Giza168, Gemmeza9, Sakha93 and Sakha94 at seeding rate 60 kg fad^{-1} in rows. Their results showed that plant height was affected significantly by five cultivars and plant height of Misr1 was average 110 cm. In Egypt, on a clay soil **Mehasen *et al.* (2014)** planted bread wheat cultivars including Gemmeza9, Giza168, Sakha94, Sids13 and Misr1 in rows, and their results indicated that plant height was affected significantly by cultivars which was 107, 99, 90 and 101 cm for Gemmeza9, Misr1, Giza168 and

Sids13, respectively. **Mehasen *et al*. (2015)** planted bread wheat cultivars including Gemmeza11, Misr2 and Sids12 in rows, and their data showed that plant height was affected significantly among each of Gemmeza11, Misr2 and Sids12 which were averaged 109.1, 107.1 and 105.6 cm, respectively. In Egypt, at two locations on a clay soil **(Sidi, 2015)** planted three bread wheat cultivars including Gemmeza11, Sids12 and Giza168 at seeding rate 60 kg fad^{-1} in rows, and his data showed that plant height was affected significantly by three cultivars which were 100, 94 and 88 cm for Gemmeza11, Sids12 and Giza168, respectively, across two locations.

2- Number of tillers:

Hanley *et al*. (1961) suggested the numerous tillers would result in greater leverage and more lodging. In contrast with them, **Pinthus (1973)** suggested that greater tiller numbers may result in better developed root systems and less lodging. In a like manner, Data of **Easson *et al*. (1993)** showed that the least lodged cultivar produced more tillers per meter square than the other three cultivars by averaged 8.5 %. Results of **Tripathi *et al*. (2003)** pointed that number of tillers per square meter at anthesis was significantly affected by 12 semi-dwarf genotypes and the lodging resist-genotypes produced fewer tillers m^{-2} at anthesis than lodged genotypes by averaged 15.4 %. They found significant ($P<0.0001$) positive correlation between tillers m^{-2} at anthesis and lodging score. They suggested that selection for lodging resistant cultivars depended on fewer tillers per unit area. By inferring data from **Crook and Ennos (1994)**, three wheat cultivars (1 resistant ; 2susceptibles) had produced the same 3.5 tiller plant^{-1} since the plant density was 400 kernels m^{-2} for all, whilst the forth susceptible variety showed less tillers plant^{-1} by 11 % when compared with the others. **Crook**

and Ennos (1995) their data indicated identical number of tillers per plant for both lodging resistance and susceptible cultivars which was around 3.33 tiller plant^{-1} at early grain filling stage. Consequently, data of **Crook and Ennos (1994, 1995)** showed similar tillers at both of resistant and susceptible cutivars at plant density of 400 kernels m^{-2} with little exceptions.

Results of **Crook and Ennos (1996)** pointed that the lodging resistant cultivar "Hereward" had produced 2.6 tiller plant^{-1}; the total number of roots was 15.4; root length was avergae 168 mm. **Berry *et al.* (2000)** found that the greater tillers number per plant of wheat had increased lodging and leads to partially countracted the root plate effect. **Berry *et al.* (2000)** observed that producing more tillers by plant, increases root plate spread but it also increases root lodging risks. **Berry *et al.* (2007)** also suggested that ideotype design for lodging-resistance wheat with proper yield was associated with 500 tiller m^{-2} (2.5 tiller plant^{-1}) that produced from 200 plants m^{-2}. However, data of **Easson *et al.* (1993)** showed, while the most severe lodged-cultivar of wheat had produced only 1.9 tiller plant^{-1} but it did not reduce the severity of lodging which had reahed 64 %.

In the absence of lodging, a set of trials in Egypt have shown the effect of cultivar on tillers number. For example, **El-Gizawy, 2005)** found that Gemmeza9 had produced the highest number of tillers per square meter when compared with either Gemmeza5 or Gemmeza7. **Abdel-Ati and Zaki, 2006)** stated that both of Giza155 and Sakha8 produced the same number of tillers per square meter at heading stage. **Gomaa *et al.* (2011)** data indicated that number of tillers per square meter at heading stage for Gemmeza7 was higher than Sakha93 by 12%. **Abdallah *et al.* (2013)** results showed that number of tillers per square meter of Gemmeza10 was averaged 559 tiller plant^{-1} and significantly more than Sakha93. Data of **Sidi (2015)** indicated that number of tillers per square meter was affected significantly by three cultivars which were 475, 496 and 639 tiller m^{-2} for Gemmeza11, Sids12 and Giza168, respectively, across two locations.

3- Shoot fresh weight per plant:

By inspecting data of **Easson *et al*. (1993)** the mediate lodged cultivar had produced the heaviest dry weight per plant at anthesis (lodging time) which was more than either the least or severe lodged cultivars by averaged 8.3 %. By inferring data from **Crook and Ennos (1994)**, three susceptible cultivars of wheat exhibited significant variability in the total shoot fresh weight at anthesis, which ranged from 9.3 to 10.9 g plant^{-1}. Shoot fresh weight for the only resistant cultivar was differed significantly when compared only with the heaviest cultivar by 8.3 % less. Their data also showed that the only resistant cultivar did not differ significantly from 2 out of 3 susceptible cultivars. Therefore we can consider that either lodging resistant or susceptible cultivars have almost similar shoot fresh weight at anthesis with little exception. By inspecting data from **Crook *et al*. (1994)**, plant fresh weight at anthesis for the lodging-resistant Hereward was lower than the susceptible Galahad. **Crook and Ennos (1995)** found also that plant fresh weight at anthesis for the susceptible Galahad was higher than the lodging-resistant Hereward. In the absence of lodging, results of **Abdel-Ati and Zaki (2006)** indicated that plant fresh weight at heading for Giza155 was 6.7 g plant^{-1} and significantly more than Sakha8 by 34%.

4- Shoot dry weight per plant:

By inspecting data of **Easson *et al*. (1993),** the least lodged cultivar produced the heaviest dry weight per plant at anthesis which was more than the severe lodged cultivars by averaged 6.3 %.**Crook and Ennos (1994)** reported that lodging resistance by cultivar was associated with lighter stems. They explained this as lighter weight reduces the forces, which applied to plants by wind and gravity. They suggested that wind-induced forces on a plant will be transmitted into the ground and may eventually cause the stem to lean permanently. Once a plant is leaning, the weight of the aerial parts of the stem will also help to pull the plant over as we indicated before. In 1990, **Stapper and Fischer**' data showed that plant dry weight at anthesis was significantly affected by four genotypes which were differed in the intensity of lodging and the lowest-lodged genotype had lighter weight than highest-lodged genotypes by at least 23.5 %. In another experiment by them, data pointed that plant dry weight at anthesis was affected significantly by twenty genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had almost lighter weight than highest-lodged genotypes in the range of 8.9 %. In another trial by them, data indicated that plant dry weight at anthesis was not affected by two genotypes that were differed in the intensity of lodging with averaged 9.6 g plant^{-1}. In another trial by them, data showed that plant dry weight at anthesis was significantly affected by sixteen genotypes and the none-lodged genotypes had produced lighter dry weight plant^{-1} than lodged genotypes by averaged 5.8 %. They mentioned that dry weight per square meter at anthesis had explained 65 % of the variation in lodging for the combined data of two experiments which were including 34 crops under a wide range of conditions. They also found a positive correlation between lodging score and dry weight per square meter at anthesis.

Results of **Tripathi *et al*. (2003)** pointed that plant dry weight at anthesis affected significantly by 12 semi-dwarf genotypes and the lodging resist-genotypes had produced heavier plants at anthesis than lodged genotypes by averaged 1.1 %. However, they found insignificant negative correlation between shoot dry weight at anthesis and lodging score. Later in 2004,**Tripathi *et al*.** reported that some of higher lodging genotypes could be related to its heavier weight of plants. For instance, Super Seri gave higher values for lodging and heavier weight of plants than Seri82 by 38.6 and 7.9 %, respectively. Data of **Tripathi *et al*. (2005)** indicated that plant dry weight was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had heavier plants than lodged genotypes by averaged 4 %.

In the absence of lodging, data of **Abdel-Ati and Zaki (2006)** indicated that plant dry weight at heading for Giza155 was 3.1 g plant^{-1} and significantly more than Sakha8 by 29%. In 2011, **Gomaa *et al*.**'s data showed that plant dry weight at heading stage for Gemmeza7 was averaged 8.9 g plant^{-1} and higher than Sakha93 by 11%. **El-Metwally *et al*. (2012)** concluded that heaviest shoot dry weight was 5.5 g plant^{-1} which was produced by Giza168 and significantly heavier when compared with the other cultivars. In Egypt, on a sandy soil **(Harb *et al*., 2012)** evaluated two bread wheat cultivars and they found that plant dry weight of Gemmeza9 was 13 g plant^{-1} and significantly heavier than Sakha93.

D) Yield and yield components:

1- Number of spikes per square meter:

By inspecting data of **Easson *et al*. (1993),** the least lodged cultivar produced more spikes per meter aquare than the other three cultivars by averaged 12.6 %. Data of **Tripathi *et al*. (2004)** data indicated that number of spikes per square meter at anthesis was significantly affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had produced fewer spikes

m^{-2} at anthesis than lodged genotypes by averaged 3.4 %. Data of **Tripathi *et al*. (2005)** showed that number of spikes per square meter was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had produced fewer spikes m^{-2} than lodged genotypes by averaged 5.1 %. Data of **(Ramburan and Greenfield, 2007)** showed that number of spikes per square meter for the susceptible variety was significantly higher than two lodging-resist varieties by average 11.5 % thus it seemed that the ability of plant to produce more fertile tillers had enhanced lodging of wheat in later stages of ripening. **Pinera-Chavez *et al*. (2016)** mentioned that spike area for spring wheat averaged by 19 cm^2 compared with 12 cm^2 for winter wheat with slightly greater yield and similar spikes m^{-2}. They commented that the absence of awns on winter wheat explains at least part of this difference. Therefore, spring wheat will have a greater leverage than winter wheat for crops at the same height, yield and spikes m^{-2}. Consequently, spring wheat is more susceptible than winter wheat by at least 22.5 % as we found from data of **Pinera-Chavez *et al*. (2016)**. Although, spike area has shown to be a useful trait for explaining the variation in root-lodging susceptibility, especially in spring wheat as shown by **(Pinera-Chavez *et al*., 2016)**, but unfortunately it was not measured in our study.

In the absence of lodging, **Noureldin *et al*. (2013)** planted four bread wheat cultivars including Gemmeza10, Sids12, Giza168 and Sakha94 in rows, on a clay soil in Egypt. Their data reveled that number of spikes per square meter was affected significantly by four cultivars which were almost around 240 spike m^{-2} for Gemmeza10, Sids12 and Giza168 but lesser at Sakha94, however the researchers did not mention the plant density that had established in their study. **Seleem and Abd-Eldayem (2013)** found that number of spikes per square meter was affected significantly by five cultivars and it was reached 387 spike m^{-2} for Misr1.

In Egypt, on a sandy soil, **(Thanaa and El-Hussin, 2013)** evaluated bread wheat cultivars including Gemmeza11, Shandaweel1, Sids12 and Sids13 at seeding rate 70 kg fad^{-1} in rows. Data showed that number of spikes per square meter was approximately 230 spike m^{-2} for each of Gemmeza11, Shandaweel1 and Sids12, but they differed significantly form Sids13 which was produced 266 spike m^{-2}. Results of **Mehasen *et al*. (2014)** indicated that number of spikes per square meter was affected significantly by cultivars which were 336, 301, 300 and 301 spike m^{-2} for Gemmeza9, Misr1, Giza168 and Sids13, respectively. Data of **Mehasen *et al*. (2015)** showed that number of spikes per square meter was affected significantly among each of Misr2, Gemmeza11, and Sids12, which were averaged 393, 380 and 372 spike m^{-2}, respectively. The number of spikes per square meter was affected significantly by three cultivars which were 318, 331 and 399 spike m^{-2} for Gemmeza11, Sids12 and Giza168, respectively, across two locations as inferred from **Sidi (2015)**.

2- Number of kernels per spike:

In 1990, **Stapper and Fischer**' data showed that number of kernels per unit area was significantly affected by four genotypes which were differed in the intensity of lodging and the lowest-lodged genotype had always fewer kernels than highest-lodged genotypes by at least 11.5 %. In another experiment by them, data pointed that number of kernels per unit area was significantly affected by twenty genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had more kernels than the highest-lodged genotypes in the range of 23 %. In another trial by them, data indicated that number of kernels per unit area was significantly affected by two genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had less kernels than highest-lodged genotype by averaged 35 %. Results of an additional trial by them indicated that either none-lodged genotypes or lodged genotypes were produced, in average, the same number of kernels per unit area. By inspecting data of **Easson *et al*. (1993),** the mediate lodged cultivar had produced more kernels per spike than the least and severe lodged cultivars by 19 % and 16.4 %, respectvely. In addition, the results of the simple linear regression model showed negative correlation (r = -0.90 and R^2 = 81 %, $P<0.05$) between the number of kernels per spike and lodging percentage. Data of **Tripathi *et al*. (2005)** showed that number of kernels per spike was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had more kernels spike^{-1} than lodged genotypes by averaged 5.4 %. Data of **Ramburan and Greenfield (2007)** showed that number of kernels per spike for the susceptible variety was significantly lower than two lodging-resist varieties by average 19.2 % but as we mentioned before the lodging of wheat was occurred at later stages of ripening thus the number of kernels did not affect by lodging. **Fischer and Stapper (1987**) examined semi-dwarf wheat (*T. aestivum* and *T. Durum*) for lodging, and found that kernels per spike were reduced when lodging had occurred at early anthesis stage, which resulted in reduction, by 35 % in grain yield.

In the absence of lodging, **Abdel-Ati and Zaki** (**2006)** mentioned that cultivars showed no significane impact on number of kernels per spike. In Egypt, on a sandy loam soil **Fateh and Abdel-Dayem (2013)**, evaluated five bread wheat cultivars and their data indicated that number of kernels per spike for Sids12 was 66.7 kernel spike^{-1} across two seasons and significantly more than Misr1 by 19.5 %. Data of **Noureldin *et al*. (2013)** showed that number of kernels per spike was affected significantly by four cultivars which were average 64, 63, 58 and 57 kernel spike^{-1} for Sids12, Gemmeza10, Sakha94 and Giza168, respectively. **Seleem and Abd-Eldayem (2013)** found that number of kernels per spike was affected significantly by five cultivars and it was reached 51 kernel spike^{-1} for Misr1. At seeding rate of 70 kg fad^{-1}, **Thanaa and El-Hussin (2013)** found that number of kernels per spike was not affected significantly among Sids12, Shandaweel1 and Gemmeza11 and it was averaged 33 kernel spike^{-1}. Data of **Mehasen *et al*. (2015)** data showed that number of kernels per spike was affected significantly among Gemmeza11, Misr2 and Sids12 which were averaged 61, 59 and 55 kernel spike^{-1}, respectively. The number of kernels per spike was affected significantly by three cultivars which were 66, 73 and 62 kernel spike^{-1} for Gemmeza11, Sids12 and Giza168, respectively, across two locations **(Sidi, 2015)**.

3- Thousand kernel weight:

In 1990, **Stapper and Fischer**' data showed that kernel weight was significantly affected by four genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had always heavier kernels than highest-lodged genotypes by 17.8 %. In another experiment by them, data pointed that kernel weight was significantly affected by twenty genotypes which were differed in the intensity of lodging and the lowest-lodged genotype had lighter kernels than highest-lodged genotypes in the range of 11.2 %. In another trial by them, data indicated that kernel weight was significantly affected by two genotypes which were differed in the intensity of lodging and the lowest-lodged genotype had heavier kernels than highest-lodged genotype by averaged 16.7 %. Results of an additional trial by them indicated that kernel weight was significantly affected by sixteen genotypes and the none-lodged genotypes had produced heavier kernels than lodged genotypes by averaged 4 %.

By inspecting data of **Easson *et al*. (1993),** the mediate lodged cultivar had produced heavy kernels than the least and severe lodged cultivars by 8 and 3.2 %, respectively. In addition, the results of the simple linear regression model showed negative correlation ($r = -0.78$ and $R^2 = 61$ %, $P<0.05$)between the thousand kernel weight and lodging percentage. Data of **Tripathi *et al*. (2005)** pointed that kernel weight was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes had heavier kernels than lodged genotypes by averaged 4.6 %. Data of **Ramburan and Greenfield (2007)** showed that thousand kernel weight for the susceptible variety was significantly higher than two lodging-resist varieties by average 8.7 % thus it seemed that the ability of plant to produce more heavy spikes had enhanced lodging of wheat in later stages of ripening. **Fischer and Stapper (1987**) examined semi-dwarf wheat species for lodging, and found that kernel weight was reduced when lodging had occurred at late anthesis stage. Data of **Berry *et al*. (2004)** showed that milk stage of wheat grains (GS 75) recorded maximum reduction in thosand kernel weight due to loddging with reductions reach 12 % less than unlodged plants.

With no lodging conditions, **Abou-Elela (2001)** found that thousand kernel weight was not affected significantly by four cultivars which were ranged from average 47 to 55.5 g . **Abdel-Ati and Zaki (2006)** mentioned that cultivars showed no significant impact on thousand kernel weight. **Fateh and Abdel-Dayem (2013)** found that thousand kernel weight of Sids12 was 52.2 g across two seasons and significantly heavier than Misr1 by 15 %. Data of **Noureldin *et al*. (2013)** indicated that thousand kernel weight was affected significantly by four cultivars in one of two successive seasons and it reached 58 g at Sids12. **Seleem and Abd-Eldayem (2013)** data showed that thousand kernel weight was affected significantly by five cultivars and it reached 48 g for Misr1. **Thanaa and El-Hussin (2013)** data indicated that thousand kernel weight was affected significantly among each of Gemmeza11, Sids12 and Shandaweel1 which were weighed 40.3, 38.9 and 38.4 g, respectively. By inferring data from **Mehasen *et al*. (2014)**, thousand kernel weight was affected significantly among each of Gemmeza9, Misr1, Giza168 and Sids13 which were weighed 44.5, 41.5, 39 and 41.3 g, respectively. In Brazil, **Alves *et al*. (2015)** conducted field trials to study the effect of three wheat genotypes including CD108, CD115 and BRS220 at plant density of 350 kernels m^{-2}. Data showed that thousand kernel weight was not affected significantly among three wheat genotypes. By inspecting data from **Mehasen *et al*. (2015)**, thousand kernel weight was affected significantly among each of Gemmeza11, Misr2 and Sids12 which were weighed average 56.2, 54.4 and 50.7 g, respectively. Thousand kernel weight was affected significantly by three cultivars which were 49, 43 and 39 g for Gemmeza11, Sids12 and Giza168, respectively, across two locations as found from **Sidi (2015)**.

4- Grain yield per faddan:

In USA, **Pumphrey and Rubenthaler (1983)** found that grain yield of the standing wheat was higher than the yield of the lodged wheat which had occurred at heading by averaged 23 % across four cultivars. **Fischer and Stapper (1987**) compared either naturally or artificially lodged plots, to plots which never lodged of semi-dwarf wheat (*T. aestivum and T. Durum*), and found that grain yield was reduced by 35 % when lodging had occurred in the first 20 days after anthesis. Lodging after anthesis reduced crop growth rate, and the adverse effect of lodging on grain yield was ascribed to this reduction in photo-assimilate supply. They mentioned also that the crop in which lodging had least effect on grain yield (7 % less) was characterized by a reduced degree of source limitation during grain filling. Data of **Knapp *et al.* (1987)** showed that grain yield of susceptible cultivar was less than the lodging-resist by 6.1 % across nitrogen rates, PGRs and years, and this little difference was due to the time of lodging was very late as we indicated before.

Data of **Stapper and Fischer (1990)** showed that grain yield was significantly affected by four genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had produced grain yield more than highest-lodged genotype by 7.5 %. In another experiment by them, grain yield was significantly affected by twenty genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had produced grain yield more than highest-lodged genotypes in the range of 12.7 %. In another trial by them, data indicated that grain yield was significantly affected by two genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had produced grain yield less than highest-lodged genotype by averaged 24.4 %. Results of an additional trial by them indicated that grain yield was significantly affected by sixteen genotypes and the none-lodged genotypes had produced grain yield more than lodged genotypes by averaged 6 %. By inspecting data from **Easson *et al.* (1993)**, the least lodged cultivar had produced the highest grain yield which was more than the mediate and severe lodged cultivars by 17.3 % and 51.3 %, respectvely. In addition, the results of the simple linear regression model showed negative correlation (r = -0.88 and R^2 = 77 %, $P<0.05$)between the grain yield and lodging percentage.

By inferring data from **Tripathi *et al.* (2004)**, grain yield was affected significantly by 16 semi-dwarf genotypes and the lodging resist-genotypes had produced higher yields than lodged genotypes by averaged 3.9 %. However, this little variation in grain yield between susceptible and lodging resistance group was probably due to late lodging occurrence that was until harvest within only three weeks. This was matched with their results as they found insignificant negative correlation between grain yield and lodging score. Data of **Tripathi *et al.* (2005)** showed that grain yield was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes produced higher grain yields than lodged genotypes by averaged 4 %. This little difference in grain yield between susceptible and lodging resistance group was probably due to late lodging occurrence that was occurred during mid to late grain filling stage. However, **Tripathi *et al.* (2005)** reported that the reduction in grain yield caused by early lodging, within 20 days after anthesis, could reach 7 to 35 %.

Berry *et al.* (2004) reported that the major reductions in grain yield occur when wheat lodged flat at anthesis or early on in grain filling stage. Grain yield losses that caused by lodging could from 31 to 80% as they mentioned. Other negative effects of lodging was including reduced grain quality, greater drying costs, slower mechanical harvest **(Berry *et al.*, 2004)**, large reductions in bread-making quality **(Berry *et al.*, 2007)** and increased susceptibility to pests and diseases (**Pinthus, 1974; Berry *et al.*, 2004). Navabi *et al.* (2006)** found that grain yield was negatively correlated with lodging scores within 140 genotypes. Data of **Ramburan and Greenfield (2007)** showed that grain yield of susceptible cultivar was less than the other lodging-resist varieties by average 15 %, and this large difference was occurred even when lodging time was very late as we indicated before. **Rajkumara (2008)** reported that wheat losses due to lodging in India, have been in the range of 12 to 66 %. **(Pinera-Chavez *et al.*, 2016)** reported that lodging grain yield reductions of wheat could be in the range of 7 – 80 %.

A set of experiments were conducted to study the impact of cultivars on grian yield in the absence of lodging conditions. **Abou-Elela (2001)** found that grain yield was affected significantly ($P<0.01$) by four cultivars which were ranged from average 908 kg fad^{-1} at Sids7 to reach 1296 kg fad^{-1} at Gemmeza7. Data of **Geleta *et al.* (2002)** indicated that grain yield was affected significantly ($P<0.01$) by twenty genotypes which were ranged from approximately 966 to 1386 kg fad^{-1}. **Allam (2005)** found that Gemmeza1 had produced the maximum grain yield while Sids7 had produced the lowest. **El-Gizawy (2005)** noticed that Gemmeza9 had produced the maximum grain yield when compared with either Gemmeza5 or Gemmeza7. **Abdel-Ati and Zaki** (**2006)** mentioned that cultivars showed no significant impact on grain yield. **Svecnjak *et al.* (2007)** reported significant variations ($P<0.05$) among three bread winter wheat cultivars in grain yield. **Stipesevic *et al.* (2009)** found significant ($P<0.05$) differences among four bread winter wheat cultivars in grain yield and either Gabi or Rapsodija were produced maximum grain yield with approximately 4 ton fad^{-1}. Data obtained by **Giambalvo *et al.* (2010)** showed that grain yield was affected significantly ($P<0.001$) by genotype and maximum grain yield was recorded by either Simeto or Valbelice which exeeded Russello by 31 %. Results of **Benin *et al.* (2012)** showed that grain yield was not affected significantly by cultivars. **El-Metwally *et al.* (2012)** concluded that highest grain yield was achieved by either Sakha93 or Gemmeza9 and significantly higher when compared with the other cultivars. **Harb *et al*. (2012)** observed that grain yield of Gemmeza9 was 1645 kg fad^{-1} and was significantly more than Sakha93 by 11%. **Haile *et al*. (2012)** planted two bread wheat cultivars including Madda and Hollandi in rows at seeding rate of approximately 63 kg fad^{-1}, and their data showed that Hollandi grain yield significantly exceeded Madda by 26 %.

Abou-Elnaga and El-Gharbawy (2013) found that grain yield varied significantly among cultivars and grain yield means for Misr1, Gemmeza9 and Sids12 were 4590, 4260 and 4215 kg fad^{-1}, respectively. **Abd-Elrazek and El-Sheshtawy (2013)** found that grain yield of Gemmeza9 was 3328 kg fad^{-1} and significantly more than Sakha93 by only 3.7 %. Results of **Abdallah *et al*. (2013)** showed that grain yield of Gemmeza10 was 1680 kg fad^{-1} and significantly more than Sakha93 by only 3 %. Data from **Fateh and Abdel-Dayem (2013)** indicated that grain yield of Sids12 was 2335 kg fad^{-1} across two seasons and significantly more than Misr1 by 7.3 %. By inferring data from **Noureldin *et al*. (2013)** grain yield was affected significantly by four cultivars which were only 1764 kg fad^{-1} at either Sids12 or Giza168. **Seleem and Abd-Eldayem (2013)** found that grain yield was affected significantly by five cultivars and it was reached 3583 kg fad^{-1} for Misr1.

In 2013, on a sandy soil, **Thanaa and El-Hussin**' data showed that grain yield was affected significantly by cultivars which was approximately 2357 kg fad^{-1} at Gemmeza11 and exceeded Shandaweel1 and Sids12 by 5.5 and 19.5 %, respectively. Data of **Mehasen *et al*. (2014)** showed that grain yield was affected significantly by cultivars which was approximately 3377 kg fad^{-1} at Gemmeza9 that exceeded Misr1, Giza168 and Sids13 by 22.7, 27.7 and 24.2 %, respectively. By inspecting data from **Mehasen *et al*. (2015)**, grain yield was affected significantly by cultivars which was averaged 2372 kg fad^{-1} at Gemmeza11 that exceeded Misr2 and Sids12 by 3.4

and 8.5 %, respectively across two seasons. Grain yield was affected significantly by three cultivars which was 2749 kg fad^{-1} at Gemmeza11 across two locations; and exceeded Sids12 and Giza168 by 7.7 and 16 %, respectively as found from **Sidi (2015)**.

5- Straw yield per faddan:

Data of **Stapper and Fischer (1990)** showed that straw yield was significantly affected by four genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had produced straw yield more than highest-lodged genotype by 7.8 %. In another experiment by them, straw yield was significantly affected by twenty genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had produced straw yield more than highest-lodged genotypes in the range of 12.9 %. In another trial by them, data indicated that straw yield was significantly affected by two genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had produced straw yield less than highest-lodged genotype by averaged 24.9 %. Results of an additional trail by them indicated that straw yield was significantly affected by sixteen genotypes and the none-lodged genotypes had produced straw yield more than lodged genotypes by averaged 5.8 %. By inspecting data from **Easson *et al*. (1993)**, the least lodged cultivar had produced the highest straw yield which was more than the mediate and severe lodged cultivars by 17.6 % and 37.6 %, respectvely. By inferring data from **Tripathi *et al*. (2005)**, straw yield was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes and the lodging resist-genotypes produced higher straw yields than lodged genotypes by averaged 4 %.

A set of trials were showing cultivar effect on the straw yield in the absence of lodging conditions. For instance, **Abdel-Ati and Zaki (2006)** stated that cultivars showed no significant differences on straw yield. Results of **Noureldin *et al*., 2013)** indicated that straw yield was affected significantly by four cultivars which was 3630 kg fad^{-1} at Sids12 and less than Giza168 by 10.2 %. **Seleem and Abd-Eldayem (2013)** data showed that straw yield was affected significantly by five cultivars and it was reached 5975 kg fad^{-1} for Misr1. By inspecting data of **Thanaa and El-Hussin**, straw yield was affected significantly by cultivars which was 2912 kg fad^{-1} at Gemmeza11 and more than Shandaweel1 and Sids12 by 18 and 19.5 %, respectively. Data of **Mehasen *et al*., 2014)** showed that straw yield was affected significantly by cultivars which was 3987 kg fad^{-1} at Gemmeza9 that was more than Misr1, Giza168 and Sids13 by 17.9, 15 and 8.5 %, respectively. By inferring data from **Mehasen *et al*. (2015)**, straw yield was affected significantly by cultivars which was 2912 kg fad^{-1} at Gemmeza11 and more than Misr2 and Sids12 by 2.3 and 5 %, respectively across two seasons. Straw yield was affected significantly by three cultivars which was 4136 kg fad^{-1} at Gemmeza11 across two locations and more than Sids12 by 10.3 % but less than Giza168 by 5 %, as inspected from **Sidi (2015)**.

6- Harvest index:

Results of **Stapper and Fischer (1990)** indicated that harvest index was affected significantly by four genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had recorded harvest index more than highest-lodged genotype by 13.5 %. In another experiment by them, harvest index was significantly affected by twenty genotypes that were differed in the intensity of lodging and the lowest-lodged genotype had recorded harvest index more than highest-lodged genotypes in the range of 8.9 %. In another trial by them, harvest index was significantly affected by two genotypes which were differed in the intensity of lodging and the lowest-lodged genotype had recorded harvest index less than highest-lodged genotype by averaged 17 %. Results of an additional study by them indicated that harvest index was significantly affected by sixteen genotypes and the none-lodged genotypes had produced harvest index more than lodged genotypes by averaged 6 %. By inspecting data of **Easson *et al*. (1993)**, either the least or mediate lodged cultivars were recording higher harvest index than the severe lodged cultivars by averaged 11.2 %. By inferring data from **Tripathi *et al*. (2005)**, harvest index was significantly ($P<0.01$) affected by 16 semi-dwarf genotypes but its value in average between lodging resistance and susceptible groups was identical.

In the absence of lodging, Data of **Abou-Elela (2001)** showed that harvest index was not affected significantly by four cultivars and was ranged from 30.5 to 31.3 %. By inferring data from **El-Gizawy (2005)**, Gemmeza9 had produced the maximum harvest index when compared with either Gemmeza5 or Gemmeza7. By inspecting data from **Abdel-Ati and Zaki (2006)**, cultivars showed no significant differences on harvest index. Data from **(Giambalvo *et al*., 2010)** showed that highest harvest index was 54 % at Valbelice while Russello was the lowest one with averaged 24 %. **Harb *et al*. (2012)** observed that harvest index of Gemmeza9 was 37 % and significantly more than Sakha93 by 8 %. Results from **Abd-Elrazek and El-Sheshtawy (2013)** showed that harvest index of Gemmeza9 was 37.79 % and significantly more than Sakha93 by only 1.5 %. Data of **Abdallah *et al*. (2013)** showed that harvest index of Gemmeza10 was 37.79 % and significantly more than Sakha93 by only 1.2 %.

By inspecting data from **Seleem and Abd-Eldayem (2013)**, harvest index was affected significantly by five cultivars and the harvest index of

Misr1 was 35.8 % and 39.5 % for the first and second seasons, respectively. Data of **Thanaa and El-Hussin, (2013)** showed that highest value of harvest index was 48.3 % at Shandaweel1 and exceeded Sids12 and Gemmeza11 by 7.2 and 7.5 %, respectively. By inferring data from **Mehasen *et al*. (2014)**, values of harvest index were 45.9, 44.4, 41.9 and 41.2 % for each of Gemmeza9, Misr1, Giza168 and Sids13, respectively. Results of **Mehasen *et al*. (2015)** showed that values of harvest index were 41.4, 41.2 and 40.5 for Gemmeza11, Misr2 and Sids12 , respectively. **Sidi (2015)** his data showed that harvest index was affected significantly by three cultivars which were 40, 41 and 35 % for Gemmeza11, Sids12 and Giza168, respectively, across two locations.

III- Effect of plant growth retardants and cultivar interactions:

A) Lodging score:

Crook and Ennos (1995) reported that lodging occurred during grain filling stage only in plots that were expected to be the least resistant such as plots of the susceptible Galahad variety without treated by growth regulators. They also found that resistant Hereward did not lodge regardless of growth regulators treatments. **Berry *et al*. (2000)** reported that matching PGR strategy with variety to achieve a proper plant height would appear to be the best way of achieving the minimum lodging score. **Berry *et al*. (2004)** mentioned that the lodging risk of semi-dwarf cultivars continues to be effectively reduced by the widespread of plant growth inhibitors. Data of **(Tripathi *et al*., 2004)**, showed that wheat lodging of 16 genotypes (7 lodging-resist; 9 susceptible) could be managed by Ethephon application at the end of stem elongation stage. Data of **(Ramburan and Greenfield, 2007)** showed that lodging score was not affected significantly by plant growth inhibitors × cultivar (2 lodging-resist; 1 susceptible) interactions in two different locations. Data of **(Sinniah *et al*., 2012)** showed that lodging resistance of rice was not affected significantly by plant growth retardants (4-dosages) × two-cultivar interactions.

B) Root characters:

1- Root plate spread:

Data of **Crook and Ennos (1995)** showed that cultivar (1 lodging-resistant; 1 susceptible) × PGRs (inhibitors) application had no significant impact on the spread of the root plate.

2- Number of roots per plant:

Results of **Crook and Ennos (1995)** indicated that cultivar × PGRs application had no significant impact on number of roots per plant.

3- Structural rooting depth, structural root diameter and root dry weight per plant:

No scientific articles were published before concerning the effect of PGR and cultivar interactions on these traits.

4- Structural root length:

Data of **Rajala *et al*. (2002)** showed that Ethephon, which was sprayed during the seedling stage on leaves, did not affect root length of 2-wheat cultivars significantly.

C) Growth:

1- Plant height:

Results of **Crook and Ennos (1995)** pointed that cultivar × PGRs application had no significant impact on plant height. Data of **Alam *et al*. (2002)** showed that wheat's height was affected significantly by plant growth inhibitor (4 doses including the control) × cultivar (Sarsabz, Soghat and S-232) interactions. Findings of **Tripathi *et al*. (2004)** showed that plant height was affected significantly ($P<0.01$) by Ethephon application × genotypes (7 lodging-resist; 9 susceptible).

2- Number of tillers per square meter:

Data of **Rajala and Peltonen-Sainio (2001)** showed that number of tillers per plant was not affected significantly by (3) plant growth inhibitors × (2) cultivar interactions. Results of **Alam *et al*. (2002)** indicated that the number of tillers per plant was affected significantly by plant growth inhibitor (4 doses including the control) × cultivar (Sarsabz, Soghat and S-232) interactions.

3- Shoot fresh weight per plant:

No scientific articles were published before concerning the effect of PGRs and cultivar interactions on the fresh weight of plant at anthesis.

4- Shoot dry weight per plant:

Data of **Tripathi *et al*. (2004)** showed that plant dry weight was not affected significantly by Ethephon application × genotypes (7 lodging-resist; 9 susceptible).

D) Yield and yield components:

1- Number of spikes per square meter:

Data of **Tripathi *et al*. (2004)** indicated that number of spikes per square meter was not affected significantly by Ethephon application × genotypes (7 lodging-resist; 9 susceptible). Results of **Ramburan and Greenfield (2007)** showed that number of spikes per square meter was not affected significantly by plant growth inhibitors × cultivar (2-lodging-resist; 1-susceptible) interactions in two different locations. Number of panicles per unit area of rice was not affected significantly by plant growth retardants (4-dosages) × two-cultivar interactions as found from **Sinniah *et al*. (2012)**.

2- Number of kernels per spike:

Number of kernels per spike was affected significantly ($P<0.01$) by Ethephon application × genotypes (7 lodging-resist; 9 susceptible) as detected from **Tripathi *et al*. (2004)**. Data of **Ramburan and Greenfield (2007)** showed that number of kernels per spike was not affected significantly by plant growth inhibitors × cultivar interactions in two different locations. Results of **Sinniah *et al*. (2012)** showed that number of grains per panicle of rice was not affected significantly by Paclobutrazole (4-dosages) × 2-cultivar interactions.

3- Thousand kernel weight:

Data of **Tripathi *et al*. (2004)** indicated that kernel weight was affected significantly ($P<0.01$) by Ethephon application × genotypes and Ethephon treatment had reduced kernel weight for lodging resistant genotype PBW343 while kernel weight of the susceptible Pavon76 genotype was increased. Thousand kernel weight was not affected significantly by plant growth inhibitors × cultivar interactions in two different locations as found from **Ramburan and Greenfield (2007)**. Data of **Sinniah *et al*. (2012)** showed that hundred grain weight of rice was not affected significantly by PGRs × cultivar interactions.

4- Grain yield per faddan:

Data of **Knapp *et al*. (1987)** showed that treated susceptible and lodging-resist wheat cultivars by CCC had improved grain yield by 7.3 and 4 %, respectively across nitrogen rates and two seasons. **Berry *et al*. (2000)** found that matching PGR strategy with variety would appear to be the best way of achieving the minimum lodging score, which resulted in higher yields. Results of **Alam *et al*. (2002)** showed that grain yield affected significantly by PGRs × cultivar interactions. Data of **Tripathi *et al*. (2004)** showed that grain yield was affected significantly by Ethephon application × (16) genotypes. Grain yield of wheat was not affected significantly by PGRs × cultivar interactions in two different locations as found from **Ramburan and Greenfield (2007)**. In Canada, **Brinkman (2012)** found that grain yield of wheat was not affected significantly by CCC application × cultivar (varied in lodging behavior) interactions for six sites and three seasons. Grain yield of rice was not affected significantly by Paclobutrazole × cultivar interactions as obtained from **Sinniah *et al*. (2012)**.

5- Straw yield per faddan:

Straw yield was affected significantly by Ethephon application × genotypes as found from **Tripathi *et al*. (2004)**. Data obtained by **Alam *et al*. (2002)** showed that straw yield was affected significantly by PGRs × cultivar interactions.

6- Harvest index:

Results of **Tripathi *et al*., 2004)** indicated that harvest index was affected significantly ($P<0.01$) by Ethephon application × genotypes. Data obtained by **Alam *et al*. (2002)** showed that harvest index was affected significantly by plant growth inhibitor × cultivar interactions.

IV- Effect of mineral nitrogen rate:

Over many decades, nitrogen fertilization has been an essential tool for increasing crop yield and quality, especially for cereals, and for ensuring maximum yield. Despite advantages of applying nitrogen for wheat crop, it can also affect root lodging indirectly. Higher nitrogen rates could increase shoot: root ratio, which could easily tend plants to lodge. Accordingly, determining proper rates of nitrogen to achieve higher yields and making lodging at very low level are very important.

A) Lodging score:

Results of **Knapp *et al*. (1987)** indicated that wheat lodging score was differed significantly between two mineral nitrogen rates of approximately 20 and 76 kg fad^{-1} (in the form of ammounium nitrate) which the last rate had enhanced lodging by 85 % more than the other rate. **Crook and Ennos (1995)** data pointed that using of approximately 100 kg N fad^{-1} had increased root-lodging susceptibility for resistant and susceptible cultivars by averaged 26.7 and 21.8 %, respectively when compared to 67 kg N fad^{-1}. They also reported that plants grown at the higher nitrogen level caused significant weaker root anchorage than plants grown at the lower nitrogen level. **Griffin**

(1998) observed that high soil residual nitrogen increased lodging slightly and its effects on crop structure which related to lodging susceptibility, was much less than seed rate in all seasons. Evidence that root lodging can be manipulating by nitrogen applications is inconsistent **(Berry *et al*., 2000)**. Data of **Tripathi *et al*. (2003)** showed that wheat lodging score was not affected significantly by nitrogen rates in the first season but in the second, it increased from 36 to 53 by increasing nitrogen rates from approximately 75 to either 100 or 125 k fad^{-1}. **Berry *et al*. (2004)** mentioned that reductions in anchorage strength at higher rates of nitrogen, tended to be smaller but still larger than the effects on crop height. **Mooney *et al*. (2006)** stated that high levels of soil mineral increased the risk of stem-lodging more than the risk of root-lodging. **Rajkumara (2008)** mentioned that high rates of nitrogen increases lodging risk via making plants taller by 10 %. Data obtained by **Brinkman (2012)** showed that wheat lodging was increased linearly by increasing mineral nitrogen rates of from approximately 42 to 57 to 72 kg fad^{-1} but theses increamentals were depended mainly on variety and environmental condition.

B) Root characters:

1- Root plate spread:

Crook and Ennos (1995) noticed that the spread of the root plate was not affected significantly by nitrogen rates of approximately 67 and 100 kg N fad^{-1} between each of lodging resistant and susceptible varieties. Further, **Griffin (1998)** found that root plate width of winter wheat was not affected significantly by nitrogen rates of approximately 0, 35 and 75 kg N fad^{-1}. Similarly, **Berry *et al*. (2000)** found that mineral nitrogen rates of approximately 85 and 118 kg fad^{-1} applied to winter wheat did not affect the root plate spread. However, they reported that lower nitrogen rates resulted in less tillers per plant. Since the spread of the root plate was positively correlated with the number of tillers per plant, therefore the size of root plate will be expected to be minimized with reducding nitrogen rates.

2- Number of roots per plant:

Results of **Crook and Ennos (1995)** indicated that using of approximately 100 kg N fad^{-1} produced averaged 6 roots plant^{-1} and significantly lower than those which were produced at 67 kg N fad^{-1} by averaged 31.3 %. **Easson *et al.* (1995)** reported that reductions in anchorage strength in response to more nitrogen can be linked with fewer roots per plant. **Griffin (1998)** found that number of roots per plant for the winter wheat was not affected significantly by nitrogen rates of approximately 0, 35 and 75 kg N fad^{-1}.

3- Structural rooting depth:

Griffin (1998) observed that rooting depth of winter wheat was not affected significantly by nitrogen rates of 0 and 35 75 kg N fad^{-1}. **Berry *et al.* (2000)** found that mineral nitrogen rates did not affect the structural rooting depth of winter wheat. **Thorup-Kristensen (2009)** pointed that deeper rooting of winter wheat was related to much lower amounts of nitrogen.

4- Structural root length:

Griffin (1998) found that root length of winter wheat was not affected significantly by nitrogen rates of approximately 0, 35 and 75 kg N fad^{-1}.

5- Structural root diameter:

Mulder (1954) indicated that the crown roots of oat plants supplied with higher rates of nitrogen were free from lignified cells beneath the epidermis when compared with those which were growth at moderate level of nitrogen. **Easson *et al.* (1995)** reported that reductions in anchorage strength in response to more nitrogen can be linked with thinner roots. **(Berry *et al.*, 2004)** mentioned that thicker roots may be caused by a greater proportion of assimilate to be partitioned to the roots.

6- Root dry weight per plant:

In the absence of lodging, data of **(Campbell *et al.*, 1977a)** showed that root dry weight of spring wheat at anthesis was affected significantly ($P<0.01$) by mineral nitrogen rates. They found that root wieght increased curvilinearly with increasing nitrogen rates under irrigation. By inferring their data, maximum root dry weight was 1.12 g plant^{-1} which produced by 75 kg N fad^{-1} and more than those were produced at 0, 25 and 50 kg N fad^{-1} by 29.1, 12.1 and 3.5 % .respectively. Moreover, the root dry weight at constituted 24.3 % oth the total plant weight at the anthesis stage. They mentioned also that, in general,between tillering and anthesis stages, nitrogen fertilizer decreased the proportion of the plant that was constituted by roots. **Rajkumara (2008)** mentioned that higher nitrogen rate may also bring out restrictions in the development of coronal roots. In addition, root anchorage of some semi dwarf wheat were found to be weakened due to application of high nitrogen rates. In general, effect of higher nitrogen on root growth is less than on shoot growth and therefore increased nitrogen supply will always result in an increased shoot : root ratio, which is conducive to lodging.

C) Growth:

1- Plant height:

Data of **Knapp *et al*. (1987)** showed that using of approximately 76 kg N fad^{-1} had increased plant height by 11.5 % when compared to 20 kg N fad^{-1} and these increases were enhanced lodging of wheat. Data of **Crook and Ennos (1995)** indicated that using of approximately 100 kg N fad^{-1} had increased plant height by 2.5 % when compared to 67 kg N fad^{-1}. **Berry *et al*. (2000)** mentioned that leverage may be reduced and root-lodging resistance will be increased by selecting short plants, but they found that nitrogen rates did not affect plant height of winter wheat**. Tripathi *et al*. (2003)** results showed that nitrogen rates ranged from approximately 75 to 125 k fad^{-1} were affecting lodging score in 1 out of 2-year of their study but plant height did not differ significantly by these rates at each of the two seasons. **Berry *et al*. (2004)** reported that high rates of nitrogen increase lodging by making plant taller. Therfore, the indirect effect of shading will decrease anchorage system and increase lodging risk.

In the absence of lodging, **Fallahi *et al*. (2008)** planted winter bread wheat at seeding rate of 52 kg fad^{-1} on a silt loam soil with nitrogen rates of approximatley 0, 13, 26 and 39 kg fad^{-1}, in Iran. Data pointed positive linear relationship ($P<0.001$) between plant height and nitrogen rates. **Benin *et al*. (2012)** studied the impact of nitrogen rates of approximately 0, 25, 50 and 75 kg N fad^{-1} on wheat at seeding rate of 350 viable kernels m^{2}, and their data showed that plant height was not affected significantly by nitrogen rates. In Egypt, **Attia *et al*. (2013)** tested nitrogen rates of approximately 50, 75 and 100 kg fad^{-1} in the form of urea on Sids12 as a bread wheat, and their data showed that plant height increased linearly when nitrogen rates increased from 50 to 100 kg fad^{-1} and it reached averaged 103 cm. In Iran, **Namvar and Khandan (2013)** tested mineral nitrogen rates of approximately 0, 43, 63 and 83 kg fad^{-1} on bread wheat at plant density of 350 plant m^{-2} in rows, and their data reveled that plant height increased linearly when nitrogen rates increased from 0 to 63 kg fad^{-1} and it reached 84 cm without significant differences from rates of 83 kg N fad^{-1}.

2- Number of tillers per square meter:

Crook and Ennos (1995) found that number of tillers was not affected significantly by nitrogen rates of 67 and 100 kg N fad^{-1} between each of lodging resistant and susceptible varieties. Data of **Griffin (1998)** showed that slight increases in lodging score accompanied with the increases in tillers per plant by 7.4 %, which induced by increase nitrogen rate from 0 to approximately 85 or 150 kg N fad^{-1}). **Berry *et al.* (2000)** found that lower nitrogen rates resulted in less tillers per plant and this expected to minimize the size of root plate which is related strongly to root lodging. **Tripathi *et al.* (2003),** their results showed that number of tillers per square meter at anthesis was not affected significantly by nitrogen rates in the first season but in the second, it increased by 5.7 % when nitrogen rates increased from approximately 75 to 100 k fad$^{-1.}$ These results were matched with the variations in lodging score that was affected only in the second season as we indicated before. **Berry *et al.* (2004)** indicated that high rates of nitrogen increase lodging by producing more tillers per plant**.**

By inspecting data from **Campbell *et al.* (1977b)**, tillers per plant of spring wheat at anthesis were affected significantly by mineral nitrogen rates ranged from approximately 0 to 25 to 50 to 75 kg fad^{-1}. Maximum 6.5 tiller plant^{-1} was produced by 50 kg N fad^{-1} and more than those which were produced at 25 and 75 kg N fad^{-1} by 15.4 and 20 % .respectively. Results of **El-Gizawy (2005)** indicated that number of tillers per square meter increased linearly when nitrogen rates increased from 25 to 100 kg fad^{-1}. Data of **Abdel-Ati and Zaki (2006)** showed that tillers per square meter had increased gradually with the increases in amount of the oragnic compost application. By inferring data from **Sidi (2015)**, number of tillers per square meter was affected significantly by nitrogen rates and there was linear relationship between tillers m^{-2} and increasing nitrogen rates from 0 to 70 kg N fad^{-1}. Number of tillers per square meter was increased linealry from average 485 to 569 tiller m^{-2} across two locations.

3- Shoot fresh weight per plant:

Crook and Ennos (1995) found that plant fresh weight was not affected significantly by nitrogen rates of 67 and 100 kg N fad^{-1} between each of lodging resistant and susceptible varieties. **Berry *et al*. (2004)** indicated that high rates of nitrogen increase lodging by producing heavy plants**.**

Abdel-Ati and Zaki (2006), their data indicated that plant fresh weight had increased gradually with the increases in amount of the oragnic compost application and these increases were in the range of 57%.

4- Shoot dry weight per plant:

Results of **Tripathi *et al*. (2003)** revealed that nitrogen rates ranged from approximately 75 to 125 k fad^{-1} affected lodging score in 1 out of 2-year of their study, but dry weight of plants at anthesis did not differ significantly by these rates at each of the two seasons. By inspecting data from **Campbell *et al*. (1977a)**, plant dry weight of spring wheat at anthesis was affected significantly ($P<0.01$) by mineral nitrogen rates. Maximum 5 g plant^{-1} was produced by 75 kg N fad^{-1} and more than those which were produced at 0, 25 and 50 kg N fad^{-1} by 39.5, 8 and 5.2 % .respectively. Data of **Campbell *et al.* (1977b)**, indicated that plant dry weight of wheat at anthesis was affected significantly ($P<0.01$) by mineral nitrogen rates. It seemed that there was linear relationship between plant dry weight and nitrogen rates ranged from approximately 0 to 75 kg N fad^{-1}. Dry weight of plants was increased in the range of 44.3 %. Similarly, dry weight of plants increased gradually with the increases in amount of the oragnic compost application as found from **Abdel-Ati and Zaki (2006)**. These increases were in the range of 55%.

5- Flag leaf area:

Data of **Abou-Elela (2001)** showed that flag leaf area was affected significantly ($P<0.01$) by nitrogen rates and there was linear relationship between flag leaf area and increasing nitrogen rates from 0 to 120 kg N fad^{-1}, where the area of flag leaf was increased linealry from average 29 to 42 cm^2. Flag leaf area increased gradually with the increases in amount of the oragnic compost application and these increases were in the range of 51%, as obtained from **Abdel-Ati and Zaki (2006)**. Also, **Benin *et al.* (2012)** observed that flag leaf length was affected significantly ($P<0.01$) by nitrogen rates. In a like manner, flag leaf area was affected significantly by nitrogen rates and there was linear relationship between flag leaf area and increasing nitrogen rates from 0 to 70 kg N fad^{-1}, as found from **Sidi (2015).** Flag leaf area was increased linealry from average 26 to 56 cm^2 across two locations.

D) Yield and yield components:

1- Number of spikes per square meter:

Berry *et al*. (2004) indicated that high rates of nitrogen increase lodging by producing more spikes per square meter. In the absence of lodging, **Somarin *et al*.** (**2010)** planted Seimareh as durum wheat in Iran, on a loamy clay soil,with nitrogen rates of approximately 0, 25, 50 and 75 kg N fad^{-1} and their data pointed that highest number of spikes per square meter could be achieved by only 25 kg N fad^{-1}. In the same country, **Abedi *et al*. (2011)** planted Shiraz as winter wheat in the rows with nitrogen rates of approximately 0, 50, 100 and 150 kg N fad^{-1}, at seeding rate of approximately 75 kg fad^{-1}. Data showed that number of spikes per square meter was enhanced gradually by increasing nitrogen rates from 0 to 150 kg N fad^{-1}, but approximatley similar number of spikes was observed at either 100 or 150 kg N fad^{-1}. In Egypt, on a loamy soil, **El-Hamdi *et al*. (2012)** tested nitrogen rates of 0, 50 and 75 kg fad^{-1} in the form of ammonium sulphate on bread wheat at seeding rate of 60 kg fad^{-1}. Data reveled that number of spikes per square meter increased linearly when nitrogen rates increased from 0 to 75 kg fad^{-1}. Number of spikes per square meter increased linearly when nitrogen rates increased from 0 to 75 kg fad^{-1} and it reached averaged 383 spike m^{-2}, as inferred from **Mehasen *et al*. (2015)**. Results of **Sidi (2015)** indicated that number of spikes per square meter was affected significantly by nitrogen rates and there was linear relationship between spikes m^{-2} and increasing nitrogen rates from 0 to 70 kg N fad^{-1}. It increased linealry from average 318 to 368 spike m^{-2} across two locations.

2- Number of kernels per spike:

In the absence of lodging, data of **Benin *et al*. (2012)** showed that number of kernels per spike was not affected significantly by nitrogen rates. **N**umber of kernels per spike increased linearly when nitrogen rates increased from 0 to 90 kg fad^{-1} and it reached 56 kernel spike^{-1}, as inspected from **Seleem and Abd-Eldayem (2013)**. Kernels per spike increased linearly when nitrogen rates increased from 0 to 75 kg fad^{-1} and it was reached averaged 59 kernel spike^{-1}, as inferred from **Mehasen *et al*. (2015)**. Results of **Sidi (2015)** indicated that kernels per spike were increased linearly by increasing nitrogen rates from 0 to 70 kg N fad^{-1}. Number of kernels per spike was increased linealry from average 61 to 72 kernel spike^{-1} across two locations.

3- Thousand kernel weight:

Results of **Griffin (1998)** showed that kernel weight of wheat was reduced by averaged 4.7 % by increasing nitrogen rates from 0 to approximately 85 or 150 kg N fad^{-1}) due to slight increase in lodging score. In the absence of lodging, **Svecnjak *et al*. (2007)** studied the effect of nitrogen rates application at approximatley 30 and 80 kg fad^{-1} on bread winter wheat, on a silt loam soil, and his data showed that high rate of 80 kg N fad^{-1} decreased thousand kernel weight significantly ($P<0.001$) by 11 % than at 30 kg fad^{-1}.

By inferring data from **Somarin *et al*. (2010)**, heaviest thousand kernel weight could be achieved by only 25 kg N fad^{-1}. In contrast with above results, **Benin *et al*. (2012)** found that thousand kernel weight was not affected significantly by nitrogen rates. By inferring data from **Namvar and Khandan (2013)**, thousand kernel weight was 43 g at either 43 or 63 or 83 kg N fad^{-1} and significantly heavier than those which weighed at rates of 0 kg N fad^{-1}. Heaviest thousand kernel weight was averaged 49 g at either 60 or 90 kg N fad^{-1}, as inspected from **Seleem and Abd-Eldayem (2013)**. Thousand kernel weight increased linearly when nitrogen rates increased from 0 to 75 kg fad^{-1} and it was reached average 54 g, as inspected from **Mehasen *et al*.**

(2015). Results of **Sidi (2015)** indicated that thousand kernel weight increased linearly by increasing nitrogen rates from 0 to 70 kg N fad^{-1}, where the thousand kernel weight was increased linealry from average 39 to 48 g across two locations.

4- Grain yield per faddan:

By inferring data from **Knapp *et al*. (1987),** using of approximately 76 kg N fad^{-1} increased lodging and grain yield by 85 and 6.1 %, respectively when compared with 20 kg N fad^{-1}, but as we indicated before the timing of lodging was very late thus, the negative impact of lodging on grain yield was at very low level. Data of **Griffin (1998)** showed that grain yield for winter wheat was reduced by the range of 6.6 % by increasing nitrogen rates from 0 to approximately 85 or 150 kg N fad^{-1}) due to slight increase in lodging score.

In Canada, **Spaner *et al*. (2000)** planted winter wheat with approximately 0, 12.5 and 25 kg N fad^{-1} in the form of ammonuim nitrate. Results showed that grain yield was linearly increased ($P<0.01$) when nitrogen rates increased from 0 to 25 kg fad^{-1} and these increases were in the range of 30 %. By inferring data from **Somarin *et al*. (2010)**, highest grain yield could be achieved by only 25 kg N fad^{-1}. In contrast with above results, **Benin *et al*. (2012)** found that grain yield was not affected significantly by nitrogen rates, probabley due to higher competion among plants that grown under dense plant population of 350 plant m^{-2}. **Haile *et al*. (2012)** studied the impact of nitrogen rates of approximately 12.5, 25, 37.5 and 50 kg fad^{-1} in the form of urea on bread wheat and their data showed that grain yield was affected significantly by nitrogen rates ($P<0.05$) and there was linear relationship between grain yield and increasing nitrogen rates from 12.5 to 50 kg fad^{-1}.

By inferring data from **Namvar and Khandan (2013)**, grain yield increased linearly by increasing nitrogen rates from 0 to 63 kg fad^{-1}, and it reached approximately 2373 kg fad^{-1} without significant differences from the rate of 83 kg N fad^{-1}. Results of **Noureldin *et al*. (2013)** indicated that grain yield was affected significantly by nitrogen rates and it was linearly increased when the rates increased from 0 to 75 kg N fad^{-1}, while with continous increase in nitrogen rates, grain yield was sharply decreased in the range of 46%. Grain yield was affected significantly by nitrogen rates and it increased linearly when the rates increased from 0 to 60 kg N fad^{-1}, but with continous increase in nitrogen rates, grain yield was significantly decreased in the range of 11.6 %, as calculated from **Seleem and Abd-Eldayem (2013)**.

By inspecting data of **Hawkesford (2014)**, the pattern of nitrogen application rates for winter wheat in England during the extended period from 1985 to 2010 (he was extracted data from Uk Department of Food and Ruler Affairs), showed that approximately 75 kg N fad^{-1} was considered as the official rate for grain yield production which was ranged from approximately 2521 to 3500 kg fad^{-1} during these periods. **Mehasen *et al*. (2015)** found that grain yield increased linearly when nitrogen rates increased from 0 to 75 kg fad^{-1}, and it was reached averaged 2303 kg fad^{-1}. Data of **Sidi (2015)** indicated that grain yield increased linearly by increasing nitrogen rates from 0 to 70 kg N fad^{-1}. Grain yield was increased linealry from average 1961 to 2919 kg fad^{-1} across two locations.

5- Straw yield per faddan:

By inferring data from **Somarin *et al*. (2010),** highest straw yield could be achieved by only 25 or 50 kg N fad^{-1}. Results of **Noureldin *et al*. (2013)** indicated that straw yield affected significantly by nitrogen rates and it linearly increased when the rates increased from 0 to 75 kg N fad^{-1}, but with continous increase in nitrogen rates, straw yield was sharply decreased in the range of 51%. Similarly, straw yield increased linearly when nitrogen rates increased from 0 to 90 kg fad^{-1} and it reached 7493 kg fad^{-1} as calculated from **Seleem and Abd-Eldayem (2013)**. **Mehasen *et al*. (2015)** found that straw yield increased linearly by increasing nitrogen rates from 0 to 75 kg fad^{-1}, and it was reached averaged 3304 kg fad^{-1}. Data of **Sidi (2015)** showed that straw yield increased linearly by increasing nitrogen rates from 0 to 70 kg N fad^{-1}. Data showed that straw yield was increased linealry from average 3391 to 4432 kg fad^{-1} across two locations.

6- Harvest index:

By inspecting data from **Giambalvo *et al*. (2010)**, harvest index was 36 % at the rate of 0 kg N fad^{-1} while was 34 % at the rate of 35 kg N fad^{-1}. By inferring data from **Somarin *et al*. (2010)**, highest harvest index could be achieved by only 25 kg N fad^{-1}. By inspecting data of **(Attia *et al*., 2013)**, harvest index was decreased linearly from 46 to 44.9 %when nitrogen rates increased from 50 to 100 kg fad^{-1}. By inferring data of **Mehasen *et al*. (2015)**, harvest index increased when nitrogen rates increased from 0 to 75 kg fad^{-1}, but these increases were in the range of only 1.8%. Data of **Sidi (2015)** pointed that harvest index increased linearly by increasing nitrogen rates from 0 to 70 kg N fad^{-1}. Harvest index was increased linealry from average 36.7 to 39.8 % across two locations.

V- Effect of plant density:

Plant population per unit area is considering as a key factor for root lodging and one of the important agronomic tools to modify competition amongst wheat plants to ensure sustainable yields. Root and shoot characters are determined greatly by plant population as well as root lodging. Yield structure of *Triticum aestivum* L is adjustable across a wide range of plant population due to the compensation ability of plants. There is much compensation between major yield components such as number of spikes per unit area, kernels per spike and 1000-kernel weight. Consequently, relationships between wheat plant density as a number of plants per meter square and lodging and/or grain yield are important and very flexible.

A) Lodging score:

Results of **Stapper and Fischer (1990)** indicated that wheat root-lodging score increased linearly from 29 to 42 to 55 by increasing plant density from 100 to 200 to 400 plants m^{-2}. Generally, reducing the number of plants per unit area causes a large reduction in the lodging risk of wheat **(Easson *et al*., 1993; Webster and Jackson, 1993; Spink *et al*., 2000)**. Previous work has shown that root lodging risk increases when plant population exceed 200 plant m^{-2} due to the failure of root anchorage system and coronal roots rotates as its windward edge below the soil surface under surface irrigation conditions **(Crook and Ennos, 1993; Sparkes *et al*., 2008)**. Data of (**Easson *et al*., 1993)** showed that increasing plant density of wheat from actual 260 plants m^{-2} to 392 plants m^{-2}, had increased the lodging percentage at early anthesis stage by the range of 40 to 67 % for the three severe lodged cultivars, whilst increased lodging percentage by 13.3 % for the least lodged cultivar. In addition, increasing plant density from actual 392 plants m^{-2} to 640 plants m^{-2}, had increased the lodging percentage at early anthesis stage by more than 75 % for the all four cultivars. Moreover, they found that the established plots by 50 plants m^{-2} had no lodging**.** They also mentioned that the effect of plant density on lodging was dominant when four cultivars had shown great variation for lodging.

Griffin (1998) established three experiments at low and high plant populations. Averaged number of plants per square meter at low densities were 100, 220 and 242 plants m^{-2}, whilst the number of plants at higher densities were averaged 226, 435 and 386 plants m^{-2} for the three experiments, respectively across two sowing dates. His data showed that low plant population reduced root-lodging risk in all experimental years by averaged 68.2 %. He suggested that number of roots and root plate spread were the crucial factors for root-lodging resistance rather than other traits. **Berry *et al*. (2000)** observed that root lodging was significantly less by more than 50 % at plant density of 250 kernel m^{-2} than density of 500 kernel m^{-2}. They concluded that controlling root-lodging must focus on minimizing the number of shoots per plant whilst widening root plate and deepening root depth. Therefore, seed rate was the best way of manipulating these characters, but improvements in the width and depth of the root plate, associated with low seed rates, were partially offset by their positive relationship with shoots per plant.

Data of **Spink *et al*. (2000)** showed that increasing plant density of wheat from 250 to 350 plants m^{-2} increased lodging area by 27 %. **Berry *et al*. (2004)** showed that root lodging increased gradually from 0 to 100% by increasing plant density from 100 to 400 plants m^{-2}. They illustrated that low ratio of red light to far-red light in the denser canopy, was linked to weak anchorage. In Japan, at lower plant population of 50 and 150 kernels m^{-2}, **Nakano and Morita (2009)** planted bread wheat in rows within ridges and did not observe any plant lodging for both plant densities of either 50 or 150 kernels m^{-2}.

B) Root characters:

1- Root plate spread:

The wider spread of root plate in winter wheat is considered as a key factor for root lodging resistance in many researches **(Berry *et al.*, 2000; Berry *et al.*, 2007; Sparkes *et al.*, 2008)**. **Griffin (1998)**'s data showed that low plant population reduced root-lodging risk in all experimental years, mainly by significant increase in the spread of the root plate by 15 – 28 %. In addition, they concluded from their prediction model, that root plate spread was found to be a crucial indicator of lodging risk acorss different plant populations. **Berry *et al.* (2000)** mentioned that plant density had the greatest influence on the spread of the root plate indicating that plant population was probably an important determinant of this character which is related mainly to root lodging as we indicated before. Data of **Berry *et al.* (2000)** showed that the spread of the root plate was reduced significantly by 22 % when plant density increased from 250 to 500 kernel m^{-2}. They also found that root plate spread variation depended mainly on the number of tillers as it increased by more tillers and vice versa. **(Berry *et al.*, 2003)** concluded that wider root plate should be always tergeted by breeders to maximize lodging resistance. In UK, on a clay soil, **Mooney *et al.* (2006)** planted winter wheat at plant density of 100 and 200 kernel m^{-2}**,** their data showed that the spread of the root plate was 59.3 mm at plant density of 100 kernel m^{-2} and reduced by 37.3 % at higher density. **Berry *et al*. (2007)** also concluded that ideotype design for lodging-resistance wheat with proper yield was associated with a root plate spread of 57 mm.

Data of **(Sparkes *et al*., 2008)** showed that the spread of the root plate was linearly decreased with increasing plant density from 11 to 495 kernel m^{-2} and plant density of 495 kernel m^{-2} had spread of 40.65 mm of the root plate which was lower than those which was produced at 171 kernel m^{-2} by 29 %. They also found that the spread of the root plate, which has been linked most strongly with anchorage strength, was almost exclusively influenced by the quantity of photosynthetically active radiation intercepted per plant at the beginning of stem extension which had taken low values when canopy increased. At this particular period, the ralationship between amount of PAR intercepction and dry matter accumulation and partitioning are critical for the determination of anchorage strength as expressed by spread of the root olate. They concluded that as the density of wheat plants increase, the spread of the root plate decrease, leading to reduced anchorage strength and increased lodging susceptibility. **Pinera-Chavez *et al*. (2016)** established 160 and 180 plants m^{-2} with approximately 85 kg N fad^{-1} to evaluate the effect of low plant populations on lodging traits. Root plate spread was found to be increased from 30 to 55 mm at lower plant density. They also mentioned same results but in another work in UK, as the spread of the root plate was 45 mm at 160 plants m^{-2} and wider than those which were produced at 180 plants m^{-2} by 44.5 %.

2- Number of roots per plant:

Pinthus (1973) mentioned that number of roots have a reasonably close correlation with root lodging. **Neenan and Spencer-Smith (1975)** reported that the number of roots did not respond to root lodging. By inspecting data of **Easson *et al*. (1993),** increasing plant density of wheat from actual 260 to 392 plants m^{-2}, had significantly decreased roots number per stem from 24.82 to 22.57 roots $stem^{-1}$ with total reduction of 9.1 % across four wheat lodged-cultivars.They also found that greater anchorage strength has been attributed to more roots per plant. **Griffin (1998)**'s results indicated that low plant population reduced root-lodging risk in all experimental years, by significantly increasing crown root number per plant by 28 %. **Whaley *et al*. (2000)** observed that establishing fewer plants resulted in plants with more crown roots. Data of **Mooney *et al*. (2006)** pointed that the number of roots per plant was 48.4 at plant density of 100 kernel m^{-2} and reduced sharply by 56.6 % at density of 400 kernel m^{-2}. In UK, on a sandy loam soil, **Sparkes *et al*. (2008)** planted winter wheat in rows at averaged plant density of 11, 45, 90, 171 and 495 kernel m^{-2}. Data showed that number of roots per plant was linearly decreased with increasing plant density and plant density of 495 kernel m^{-2} had produced 23 roots $plant^{-1}$ which was lower than those which produced at 171 kernel m^{-2} by 49 %. **Sparkes *et al*. (2008)** mentioned that as the density of wheat plants increased, the number of roots per plant decreases, leading to reduced anchorage strength of the root-soil system and increased root-lodging susceptibility. They also found that the number of roots per plant was influenced by both the quantity and quality of light, which are called photosynthetically active radiation (PAR) and the ratio of red to far red light

(R : FR), respectively, thus at dense canopy, the light intercepted by plants will reduce, leading to the root number reduction.

3- Structural rooting depth:

In UK, **Kirby (1993)** mentioned that reducing root lodging is probably caused by the plant's ability to adjust its crown depth to more than 40 mm. Results of **Griffin (1998)** indicated that low plant population reduced root-lodging risk, by significant increase in rooting depth. Moreover, they suggested that rooting depth considered as a crucial indicator of lodging risk acorss different plant populations. **Berry *et al.* (2000)** found that rooting depth at plant density of 250 kernel m^{-2} was deeper than those which were established at density of 500 kernel m^{-2}. Structural rooting depth was average 40 mm and extended by 5 mm on average at the lower plant density when compared with the higher density. They also mentioned that increase in rooting depth increases anchorage and root lodging resistance. **Berry *et al.* (2003)** concluded that deeper roots should be targeted by breeders to maximize lodging resistance.

4- Structural root length:

By inspecting data of **Easson *et al.* (1993)**, increased plant density of wheat from actual 260 to 392 plants m^{-2}, significantly decreased structural root length from 58.11 to 53.85 mm with total reduction of 7.3 % across four wheat lodged-cultivars. In addition, these densities produced similar length of the non-structural roots with averaged 10.4 mm. Data of **Griffin (1998)** showed that structural root length of wheat was not affected significantly by actual plant density of either 100 or 226 plants m^{-2}. However, they found in another experiment that plant density of 220 plants m^{-2} had produced root length as twice than those at plant density of 435 plants m^{-2}. **Berry *et al.***

(2000) concluded that structural root length differed significantly by plant density. Data of **Sparkes *et al.* (2008)** showed that length of the structural roots was linearly decreased with increasing plant density from 11 to 495 kernel m^{-2} and plant density of 495 kernel m^{-2} had produced total length of 80 mm which was lower than those which produced at 171 kernel m^{-2} by 62 %. They found that length of the structural roots was influenced by the amount of photosynthetically active radiation and the ratio of red to far red light, thus at dense canopy, the light intercepted by plants will reduce, leading to the root length reduction. Their data also indicated that length of the non-structural roots was linearly decreased with increasing plant density from 11 to 495 kernel m^{-2} and plant density of 495 kernel m^{-2} had produced total length of 60 mm which was lower than those which produced at 171 kernel m^{-2} by 67 %. They found that length of the non-structural roots was influenced by the amount of photosynthetically active radiation, thus at dense canopy, the light intercepted by plants will be reduced, leading to the root length reduction.

5- Structural root diameter:

Pinthus (1973) mentioned that diameter of roots have a reasonably close correlation with root lodging. On the other hand, **Neenan and Spencer-Smith (1975)** reported that the root diameter was not the most great response for root lodging. However, the greater anchorage strength has been attributed to thicker roots **(Easson *et al.*, 1995)**. **Berry *et al.* (2004)** reported that thicker roots may be caused by the absence of a strong shade avoidance response by the plant, which stimulates a greater proportion of assimilate to be partitioned to the roots. **Berry *et al.* (2000)** defined the structural root parts as the sections of roots surrounded by a rhizosheath. **Sparkes *et al.* (2008)** reported that the presence of a rhizosheath has previously been associated with secondary lignification and with mechanical strength of resistance against root lodging. In addition, they found that average structural root diameter had decreased from 0.838 to 0.646 mm ($P<0.01$) as the plant density increased from 46 to 530 plants m^{-2}. This reduction in root diameter by 23 % at higher canopy would certainly reduce the root mechanical strength of resistance against lodging.

6- Root dry weight per plant:

Roots of wheat are poor competitors to other organs when there is a limited supply of available carbohydrates **(Rawson and Hofstra, 1967)** as light intensity decreases at higher plant densities. Root: shoot ratio rises as light intensity increases, this was mentioned by **Nelson (1963)**. Thus, this ratio is expected to decrease under dense plant population due to low light intensity. Increasing canopy shade at higher plant population will reduce the quantity and quality of light, leading to affecting the amount of available assimilates for producing structural root material or the root dry weight as understood from **Sparkes *et al*. (2008).**

By inspecting data from **Easson *et al*. (1993)**, increasing plant density of wheat from actual 260 to 392 plants m^{-2}, significantly decreased root dry weight per stem from 654 g to 414 mg $stem^{-1}$ with total reduction of 36.7 % across four wheat lodged-cultivars.They also found that weaker anchorage strength has been attributed to a lower root dry weight per stem. **Berry *et al*. (2007)** indicated that root biomass increased by 67 % at plant density of 135 plants m^{-2} when compared with those that were established by 225 plants m^{-2}. Root dry weight was found to be increased from 200 to 600 mg $plant^{-1}$ by reducing plant density from 180 to 160 plant m^{-2}. They also mentioned same results but in another work in UK, as plant population were 160 and 180 plants m^{-2}; root dry weight was 400 mg at 160 plants m^{-2} and heavier than those which were produced at 180 plants m^{-2} by 75 %.

C) Growth:

1- Plant height:

Data of **Easson *et al*. (1993)** showed that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, significantly decreased plant height by 30.7 % across four wheat lodged-cultivars. **Griffin (1998)** concluded from their prediction model, that plant height was found to be unimportant indicator of lodging risk acorss different plant populations. **Berry *et al*. (2000)** mentioned that leverage may be reduced and root-lodging resistance will be increased either by selecting short varieties or applying plant growth regulators, but they found that low plant density did not affect plant height of wheat when compared with dense densities**. Berry *et al*. (2003)** found that breeders often use visual observations of shorter plants to maximize lodging resistance but this trait was less important than at least four parameters. **Berry *et al*. (2007)** concluded that ideotype design for lodging-resistance wheat with proper yield was associated with plant height of 0.7 m. In Pakistan, **Hussain *et al*. (2001)** planted wheat at seeding rates of approximately 42, 52.5 and 63 kg fad^{-1} which theoretically about equivalent to 230, 290 and 350 kernels m^{-2}, respectively and their results showed that plant height was averaged 102 cm without significant differences among these densities.

In USA, at four environments, **Geleta *et al*. (2002)** planted winter wheat genotypes in rows at seeding rates of approximately 7, 14, 28 and 56 kg fad^{-1} which theoretically equivalent to 50, 100, 200 and 400 kernels m^{-2}. Results showed that highest plant height was averaged 87.5 cm at plant density of 200 kernels m^{-2} and significantly taller than those which were produced at 400 kernels m^{-2} by only 1.4 %. **Nakano and Morita (2009)** data showed similar culm length at plant density of either 50 or 150 kernels m^{-2} with average 73 cm. In Pakistan, **(Baloch *et al*., 2010)** planted wheat in rows at seeding rates of approximately 42, 52.5, 63, 73.5 and 84 kg fad^{-1} which theoretically equivalent to 260, 325, 390, 455 and 520 kernels m^{-2}. Data showed that plant height was 93 cm at plant density of 455 kernels m^{-2} and significantly taller than densities of 260 and 325 but the marginal differences did not exceed 2.5 %. In Pakistan, **UIIah (2014)** planted wheat in rows at seeding rates of approximately 21, 31.5, 42, 52.5, 63 and 73.5 kg fad^{-1}, which theoretically equivalent to 120, 180, 240, 300, 360 and 420 kernels m^{-2}. His data showed that maximum plant height was averaged 103 cm at plant density of 420 kernels m^{-2} and significantly more than densities of 240 and 360 by 10.4 and 3.6 %, respectively.

2- Number of tillers per square meter:

Data of **Easson *et al.* (1993)** showed that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, increased the number of tillers per square meter by 11.1 % across four wheat lodged-cultivars. **Griffin (1998)** results indicated that low plant population (220 plants m^{-2}) significanlty reduced root-lodging risk, with significantly increasing tillers per plat by 37.5 % when compared with established canopy at 435 plants m^{-2}. **Berry *et al.* (2000)** found positive correlation between number of tillers per plant and the spread of the root plate. At lower plant densities, root plate spread will increase which mainly increases lodging resistance, but when tillers increased per plant at these densities, partial counteracted with the root plate effect will be detected (**Berry *et al*., 2000)**. However, plant density of 392 plants m^{-2} produced only 1.5 tiller plant^{-1} but the severity of lodging reached 67 % more than those which were established by 260 plants m^{-2} and produced 1.9 tiller plant^{-1}, as calculated from **Easson *et al*. (1993)**. Consequently, less tillers did not improve lodging resistance in their study. **Berry *et al*. (2000)** also mentioned that root lodging was less at lower plant population and this could be related to the late forming tillers which were having small spikes at these densities. Their data also showed that plant density of 500 kernel m^{-2} had decreased the number of tillers per plant by 37.5 % when compared with density of 250 kernel m^{-2}**.**

Whaley *et al*. (2000) found that lower populated plants have many tillers, each of which developed up to four crown roots from each of their subterranean nodes. Therefore, it should be of no surprise that establishing fewer plants results in plants with more crown roots. **Berry *et al*. (2003)** concluded that less tillers per plant should be targeted to maximize lodging resistance. **Berry *et al*. (2004)** reported that strongest anchorage systems were supported by 2 to 3 shoots per plant whilst the weak anchorage could be supported by more than 3 shoots plant^{-1} which were produced from fewer plants per square meter. Later in 2007, **Berry *et al*.** concluded that ideotype design for lodging-resistance wheat with proper yield was associated with 500 tiller m^{-2} (2.5 tiller plant^{-1}) from 200 plants m^{-2}. In USA, **Chen *et al*. (2008)** found greater mortalities of tillers at higher plant densities such as 323 or 430 kernels m^{-2}. Results of **Baloch *et al*. (2010)** showed that number of tillers per square meter was average 303 tiller at plant density of 455 kernels m^{-2} and higher than those which produced at 260 and 325 kernels m^{-2} by 10.8 and 6.8 %, respectively.

3- Shoot fresh weight per plant:

By inspecting data of **Easson *et al*. (1993)**, increasing plant density of wheat from actual 260 to 392 plants m^{-2}, significantly decreased plant fresh weight from 24.56 g to 17.36 g with total reduction of 29.3 % across four wheat lodged-cultivars. They also found that weaker anchorage strength has been attributed to less fresh weight per plant**.**

4- Shoot dry weight per plant:

By inferring data from **Stapper and Fischer (1990)**, dry weight of plant at anthesis was significantly lower at plant density of 200 plants m^{-2} (less lodged) by 4.8 % when compared with those which were produced at plant density of 400 plants m^{-2} (high-lodged). Results of **Easson *et al*. (1993)** indicated that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, had significantly decreased plant dry weight from 5.13 g to 3.61 g with total reduction of 29.6 % across four wheat lodged-cultivars.

In Pakistan, **Wajid *et al*. (2004)** planted wheat in rows at plant density of 200, 300, and 400 plants m^{-2} and their results showed that plant densities of either 200 or 300 or 400 plants m^{-2} had produced similar dry matter weight per square meter at anthesis and this could be strong indicator that at lower densities, individual plant dry weight was higher than those which were produced at higher densities. In Denmark, **Olsen *et al*. (2005)** planted spring wheat in rows under weed conditions at plant density of 204, 449 and 721 kernels m^{-2}. By inferring their data, maximum dry weight of plant at anthesis was produced at density of 204 plants m^{-2} which was exceeded those which were produced at 449 plants m^{-2} by more than twofold. In Italy, **Arduini *et al*. (2006)** planted durum wheat in rows at plant densities of 200, 250 and 400 kernels m^{-2} and by inferring their data, dry weight of plant had weighed 6.2 g at plant density of 250 kernels m^{-2} and significantly heavier than densities of 400 by 26.6 %. Results of **Nakano and Morita (2009)** indicated that heaviest dry weight of plant at anthesis was approximately 13 g at plant density of 50 kernels m^{-2}, while it decreased by 62 % at density of 150 kernels m^{-2}.

5- Flag leaf area:

No scientific articles were found concerning the effect of plant density on this trait.

D) Yield and yield components:

1- Number of spikes per square meter:

Data of **Easson *et al*. (1993)** showed that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, increased number of spikes per square meter by 24.3 % across four wheat lodged-cultivars. **Spaner *et al*. (2000)** planted winter wheat in rows at plant density of 255, 320, 385 and 450 kernels m^{-2}. In the absence of lodging conditions, results of the first season showed that maximum number of spikes per square meter was average 483 spike m^{-2} at plant density of either 320 or 385 or 450 kernels m^{-2} and significantly ($P<0.05$) higher than those which produced at 255 kernels m^{-2} by 15.2 %. However, all these densities produced the same 610 spike m^{-2} in average for the second season. Results of **Hussain *et al*. (2001)** showed that number of spikes per square meter increased linearly by increasing plant density from 230 to 350 kernels m^{-2} by 10.7 %. In Spain, on a loam soil, **Lloveras *et al*.** (**2004)** planted wheat in rows at plant density of 150, 175, 250, 300, 400 and 500 kernels m^{-2} and their results showed similar number of spikes per square meter at plant densities of either 250 or 300 or 400 or 500 kernels m^{-2} which had reached a round 500 spikes m^{-2} under favourable conditions.

In USA, on a silt loam soil, **Schillinger (2005)** planted spring wheat in rows at plant density of 120, 200 and 280 kernels m^{-2} and their results indicated that number of spikes per square meter was increased linearly with increasing plant densities ranged from 120 to 280 kernels m^{-2}. However, these differences were not significant. By inferring data from **Arduini *et al*. (2006)**, number of spikes per square meter was 563 spike m^{-2} at plant density of 400 kernels m^{-2} and significantly more than those which were produced at 250 kernels m^{-2} by 19.5 %. On a loamy soil, **Chen *et al*. (2008)** planted spring wheat in rows at plant densities of 108, 215, 323 and 430 kernels m^{-2}. Results showed that maximum number of spikes per square meter was averaged 394 spike m^{-2} at plant density of 430 kernels m^{-2} and higher than those which were produced at 215 and 323 kernels m^{-2} by averaged 20.2 and 9.4 %, respectively.

By inspecting data from **Nakano and Morita (2009)**, maximum number of spikes per square meter was 331 spike at plant density of 150 kernels m^{-2} and higher than those which were produced at 50 kernels m^{-2} by 25 %. **Somarin *et al*. (2010)** planted durum wheat in rows at plant densities of 300, 350 and 400 kernels m^{-2} and their results pointed that number of spikes per square meter was gradually increased by increasing plant density. **UIIah (2014)** results showed that number of spikes per square meter was average 437 spike m^{-2} at plant density of 360 kernels m^{-2} and higher than those which were produced at 240 and 420 kernels m^{-2} by 32 and 6.4 %, respectively. Consequently, the reduction in number of spikes per square meter at low plant densities was much more than those at high densities and this variation may be explained due to enhancing the fertility of tillers rather than tillers generative capacity by plants at dense plant densities and vice versa for lower densities.

2- Number of kernels per spike:

Stapper and Fischer (1990) found that number of kernels per unit area at plant density of 200 plants m^{-2} (less lodged) was similar to those which were produced at plant density of 400 plants m^{-2} (high-lodged). Data of **Easson *et al*. (1993)** showed that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, decreased the number of kernels per spike by 30.7 % across four wheat lodged-cultivars. Results of the first season from **Spaner *et al*. (2000)** showed, that plant densities ranged from 255 to 450 kernels m^{-2} produced similar number of kernels per spike which was averaged 31 kernel while it was decreased significantly ($P<0.05$) by 12.3 % at plant density of 450 kernels m^{-2} when compared with plant densities of either 255 or 320 kernels m^{-2}. **Whaley *et al*. (2000)** found that the number of kernels per spike increased by 50 % for wheat plants when plant density decreased from 338 to 19 plants m^{-2}. Data of **Hussain *et al*. (2001)** indicated that number of kernels per spike decreased linearly by increasing plant density from 230 to 350 kernels m^{-2} by 9 %.

By inferring data from **Lloveras *et al*.** (**2004)**, similar number of kernels per spike at plant densities of either 250 or 300 or 400 or 500 kernels m^{-2} which it had reached average 37 kernel spike^{-1} under favourable conditions. Results of **Schillinger (2005)** indicated that number of kernels per spike was declined with increasing plant densities ranged from 120 to 280 kernels m^{-2}. However, these differences were not significant with averaged 25 kernel spike^{-1}. By inspecting data from **Arduini *et al*. (2006)**, number of kernels per spike was 27.9 kernel spike^{-1} at plant density of 250 kernels m^{-2} and significantly more than those which were produced at 400 kernels m^{-2} by 7.5 %. **Chen *et al*. (2008)** results showed that number of kernels per spike was average 33.5 kernel spike^{-1} at plant density of 215 kernels m^{-2} and higher than those which were produced at 323 and 430 kernels m^{-2} by averaged 7.2 and 14.8 %, respectively. Data of **Nakano and Morita (2009)** showed that maximum number of kernels per spike was 42.5 kernel at plant density of 50 kernels m^{-2} and higher than those which were produced at 150 kernels m^{-2} by 25.5 %. Results of **UIlah (2014)** pointed that number of kernels per spike was averaged 48 kernel spike^{-1} at plant density of whether 240 or 360 kernels m^{-2} which was higher than those which were produced at 420 kernels m^{-2} by averaged 7.3 %.

3- Thousand kernel weight:

Stapper and Fischer (1990) found that kernel weight at plant density of 200 plants m^{-2} (less lodged) was similar to those that were produced at plant density of 400 plants m^{-2} (high lodged). Data of **Easson *et al*. (1993)** showed that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, decreased thousand kernel weight by 6.4 % across four wheat lodged-cultivars. Results of **Spaner *et al*. (2000)** showed similar thousand kernel weight at plant densities ranged from 255 to 450 kernels m^{-2} with average 40.5 g across two seasons. Data of **Hussain *et al*. (2001)** indicated that thousand kernel weight did not differ significantly by plant densities that were ranged from 230 to 350 kernels m^{-2} with avergae 42 g. By inspecting data from **Geleta *et al*. (2002)**, thousand kernel weight was averaged 31.4 g at plant density of 200 kernels m^{-2} and significantly more than those which were produced at 400 kernels m^{-2} by only 4.1 %. Thousand kernel weight reached 29.2 g at plant density of either 250 or 350 plant m^{-2}, but the weight was declined by 3.4 % at 450 plant m^{-2} when compared with the others, as calculated from **Lemerle *et al*. (2004)**.

Results of **Lloveras *et al*. (2004)** indicated similar thousand kernel weight at plant densities of either 250 or 300 or 400 or 500 kernels m^{-2}; and were reached average 45 g under favourable conditions. However, data of **Schillinger (2005)** showed that thousand kernel weight was not affected by plant densities that ranged from 120 to 280 kernels m^{-2}; and it weighed averaged 30 g. By inspecting data from **Arduini *et al*. (2006)**, thousand kernel weight was the same at either plant density of 250 or 400 kernels m^{-2}. **Chen *et al*. (2008)** found similar thousand kernel weight at plant density of either 215 or 323 or 430 kernels m^{-2}, with average 25 g. **Nakano and Morita (2009)** found similar thousand kernel weight at plant density of either 50 or 150 kernels m^{-2}, with average 38 g. Similarly, **Baloch *et al*. (2010)** observed similar thousand kernel weight at plant density of either 260 or 325 or 455 kernels m^{-2} with averaged 38 g. **Somarin *et al*. (2010)** found that thousand kernel weight was decreased gradually with increasing in a plant density from 300 to 400 kernels m^{-2}. In a like manner, thousand kernel weight was decreased gradually with increasing plant density from 240 to 360 to 420 kernels m^{-2} by average 10.4 and 22.5 %, respectively as calculated from **UIIah (2014)**.

4- Grain yield per faddan:

Stapper and Fischer (1990) found that grain yield was not affected by plant density that ranged from 100 to 200 to 400 plants m^{-2}, which were induced significant differences in the intensity of root lodging. Data of **Easson *et al*. (1993)** showed that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, had decreased grain yield by 25.6 % across four wheat lodged-cultivars. They concluded that the decline in yield with increased lodging and plant density was attributed to the effect of lodging rather than to plant density; and was associated with the fall in kernels spike^{-1} and thousand-kernel weight. Results of **Spaner *et al*. (2000)** showed that grain yield increased linearly when plant density increased from 255 to 450 kernels m^{-2} and these increases were in the range of 20 and 9.5 % in the first and second season, respectively. In Denmark, **Weiner *et al*. (2001)** planted spring wheat in rows at plant density of 200, 400, and 600 kernels m^{-2}. Results showed that grain yield was approximately 3601 kg fad^{-1} at plant density of 400 kernels m^{-2} and was significantly ($P<0.001$) fourfold more than those which were produced at plant density of 200 kernels m^{-2} due to the negative impact which was induced by weeds at the last one. Data of **Hussain *et al*. (2001)** indicated that grain yield increased linearly by increasing plant density from 230 to 350 kernels m^{-2}; by at least 11 %. By inspecting data from **Geleta *et al*. (2002)**, grain yield was similar at plant density of either 200 or 400 kernels m^{-2} with approximately 1345 kg fad^{-1} across 20 genotypes and four environments. However, this similarity was particular for 2 out of 4 environments while each of these densities surpassed each other in grain yield by at least 12 % depening on the other two environments. **Carr *et al*. (2003)** and **Wood *et al*. (2003)** found that grain yield increased at density of 250 than 450 kernels m^{-2}.

In Australia, **Lemerle *et al*. (2004)** mentioned that the recommended plant densities were 100 to 150 plant m^{2} but they used plant densities ranged from 50 to 450 plant m^{-2} to evaluate wheat under weed conditions. Results showed that grain yield at plant density of 250 plant m^{-2} was more than those which were achieved at 350 and 450 plant m^{-2} by only 1.3 and 3 %, respectively under weed-free conditions but yield loss due to weeds were 15, 12.5 and 9.3 %, respectively for these densities. Therefore, increasing crop competitiveness using higher plant densities had found as a useful tool for weed management and increasing grain yield. Results of **Lloveras *et al*. (2004)** indicated similar grain yield at plant densities of either 250 or 300 or 400 or 500 kernels m^{-2}; and it was reached approximately above 3200 kg fad^{-1} under favourable conditions. Similar grain yield was produced at plant densities of either 200 or 300 or 400 plants m^{-2} in the first season but in the second, grain yield at plant density of 400 plants m^{-2} was significantly higher than those which were produced at 300 and 200 plants m^{-2} by 3.8 and 8 %, respectively, as calculated from **Wajid *et al*. (2004)**. Results of **Olsen *et al*. (2005)** pointed that grain yield was approximately above 3090 kg fad^{-1} at plant density of 449 kernels m^{-2} and significantly ($P<0.001$) more by average 22 % than those which achieved at plant density of 204 kernels m^{-2} due to the negative impact which induced by weeds at the last one. However, data of **Schillinger (2005)** indicated that grain yield was not affected by plant densities ranged from 120 to 280 kernels m^{-2} and it reached approximately 840 kg fad^{-1}. Thus, only 120 kernels m^{-2} were adequate to produce optimum grain yield. By inspecting data from **Arduini *et al*. (2006)**, grain yield was approximately averaged 2681 kg fad^{-1} at plant density of 400 kernels m^{-2} and higher than those which were achieved at 250 kernels m^{-2} by 17.7 %.

In Denmark, **Olsen *et al*. (2006)** planted spring wheat in rows under weed conditions at plant density of 204, 449 and 721 kernels m^{-2} and their data showed that grain yield was approximately 3056 kg fad^{-1} at plant density of 449 kernels m^{-2} and more by 5 % than those which were achieved at plant density of 204 kernels m^{-2}. In Pakistan, **Khan and Marwat (2006)** planted wheat in rows at plant densities of 280, 336, 392 and 448 kernels m^{-2} and their results showed that grain yield was approximately averaged 1325 kg fad^{-1} at plant density of 336 kernels m^{-2} and higher than similar yields which were achieved at either 280 and/or 448 kernels m^{-2} by average 7.8 %. Similar grain yield at plant density of either 215 or 323 or 430 kernels m^{-2} with approximately 1023 kg fad^{-1} as calculated from **Chen *et al.* (2008)**. Consequently, density of 215 kernels m^{-2} was proper for optimum grain yield.

In China, on a loamy clay soil **Gao *et al.* (2009)** planted winter wheat at seeding rates of approximately 75 and 95 kg fad^{-1} and their data showed that seeding rate of 95 kg fad^{-1} had produced maximum grain yield which was higher than the yield of the lower density by 5.3 %. Similar grain yield at plant density of either 50 or 150 kernels m^{-2} with approximtely 1596 kg fad^{-1} was inspected from **Nakano and Morita (2009)**. Thus, 50 kernels m^{-2} was adequate for producing optimum grain yield. Also, Similar grain yield at plant density of either 260 or 325 or 455 kernels m^{-2} with averaged 2048 kg fad^{-1} was inspected from **Baloch *et al.* (2010)**. Grain yield increased linearly with increasing plant density from 300 to 400 kernels m^{-2}, as found from **Somarin *et al.* (2010)**. In Egypt, on a sandy soil, **Abd-El-Nasser and Balah (2011)** planted bread wheat under weed conditions at seeding rates of approximately 50, 65 and 80 kg fad^{-1} which theoretically equivalent to 250, 325 and 400 kernels m^{-2}. Results showed that grain yield which produced at plant density of 250 kernels m^{-2} was similar to those at density of 325 kernels m^{-2}, but significantly lower than those which were produced at plant density of 400 kernels m^{-2} due to the negative impact that induced by weeds. Grain yield was approximately averaged 2187 kg fad^{-1} at plant density of 360 kernels m^{-2} and higher than similar yields which were achieved at either 240 and/or 420 kernels m^{-2} by averaged 15.3 %, as calculated from **UIIah (2014)**.

5- Straw yield per faddan:

Results of **Stapper and Fischer (1990)** showed that straw yield was not affected by plant density ranged from 100 to 200 to 400 plants m^{-2} that induced significant differences in the intensity of root lodging. Data of **Easson *et al.* (1993)** indicated that increasing plant density of wheat from actual 260 to 392 plants m^{-2}, decreased straw yield by 16.5 % across four wheat lodged-cultivars. By inspecting data of **Spaner *et al.* (2000)**, straw yield was linearly increased ($P<0.01$) when plant densities increased from 255 to 450 kernels m^{-2} and these increases were in the range of 20.2 %. However, data of **Schillinger (2005)** showed that straw yield was declined linearly with increasing plant densities ranged from 120 to 280 kernels m^{-2} but these differences were not significant and the straw yield was approximately 1050 kg fad^{-1}. Thus, only 120 kernels m^{-2} were adequate to produce optimum straw yield.

By inferring data from **Chen *et al.* (2008)**, similar straw yield was produced at plant density of either 215 or 323 or 430 kernels m^{-2} with approximately 995 kg fad^{-1}. Data of **Gao *et al.* (2009)** showed that seeding rate of 95 kg fad^{-1} were produced maximum straw yield which was higher than those produced at seeding rate of 75 kg fad^{-1} by 7.1 %. By inspecting data from **Somarin *et al.* (2010)**, straw yield increased linearly with increasing in a plant density from 300 to 400 kernels m^{-2}. Results of **Abd-El-Nasser and Balah (2011)** indicated that straw yield which was produced at plant density of 250 kernels m^{-2} was similar to those at density of 325 kernels m^{-2}, but significantly lower than those which were produced at plant density of 400 kernels m^{-2}. Data of **UIIah (2014)** showed that straw yield was approximately averaged 3053 kg fad^{-1} at plant density of 420 kernels m^{-2} and higher than those which were produced at 240 and 360 kernels m^{-2} by averaged 26.4 and 12.6 %, respectively.

6- Harvest index:

Results of **Stapper and Fischer (1990)** showed that harvest index was linearly decreased from 40.3 to 38.4 to 36.6 by increasing plant density from 100 to 200 to 400 plants m^{-2} that induced significant differences in the intensity of root lodging. By inferring data from **Easson *et al.* (1993)**, increasing plant density of wheat from actual 260 to 392 plants m^{-2}, decreased harvest index by 4.7 % across four wheat lodged-cultivars**.** By inspecting data of **Spaner *et al.* (2000)**, harvest index was averaged 42.5 % across two seasons and was not affected significantly by plant densities that ranged from 255 to 450 kernels m^{-2}. Data of **Schillinger (2005)** showed that harvest index was not affected by plant densities ranged from 120 to 280 kernels m^{-2} and it was calculated by averaged 44.4 %. In a same manner, results of **Chen *et al.* (2008)** showed similar harvest index (averaged 36.2 %) at plant density of either 215 or 323 or 430 kernels m^{-2}. Similarly, data of **Gao *et al.* (2009)** showed similar harvest index at seeding rates of either 75 or 95 kg fad^{-1}. Maximum harvest index was at plant density of 350 kernels m^{-2} and more by 9 % when compared with those which were obtained at either 300 or 400 kernels m^{-2}, as calculated from **Somarin *et al.* (2010)**. Data of **UIIah (2014)** showed that harvest index was averaged 38 % at both densities of 240 and 360 kernels m^{-2} and exceeded those which were obtained at 420 kernels m^{-2} by averaged 16.3 %.

VI- Effect of nitrogen and plant density interactions:

A) Lodging score:

Data of **Griffin (1998)** indicated that lodging scores for winter wheat were affected significantly by plant density (220 and 435 plants m^{-2}) × nitrogen rates (approximately 0 and 85 kg N fad^{-1}). Maximum lodging score observed at higher plant density and nitrogen rate, while plots were never be lodged at lower plant population and less nitrogen rate. In another experiment by them, lodging scores for wheat were not affected by plant density (100 and 226 plants m^{-2}) × nitrogen rates (0 and 35 kg N fad^{-1}). Results of **Nakano and Morita (2009)** showed that plant lodging was not affected significantly by plant density (50 and 150 kernels m^{-2}) × nitrogen rate (0, 30 and 38 kg N fad^{-1}) interactions.

B) Root characters:

1- Root plate spread:

Berry *et al*. (2000) found significant ($P<0.05$) interaction between plant density and nitrogen rates on the spread of the root plate. They mentioned that the spread of the root plate was not increased by reducing plant population (250 kernel m^{-2}) when nitrogen rate was at higher level (more than 100 kg N fad^{-1}).

2- Number of roots per plant, structural rooting depth, structural root diameter and root dry weight per plant:

No scientific articles were published before concerning the effect of plant density and nitrogen rate interactions on these traits.

3- Structural root length:

Griffin (1998) showed that root length doubled for winter wheat at plant density of 220 with 0 kg N fad^{-1} when compared with those, which were produced at density of 435 plants m^{-2} 85 kg N fad^{-1}.

C) Growth:

1- Plant height:

Nakano and Morita (2009) found that culm length was not affected significantly by plant densities × nitrogen rate interactions.

2- Number of tillers per square meter and shoot fresh weight per plant:

No scientific articles were found concerning the effect of plant density and nitrogen rate interactions on the tillers per square meter.

3- Shoot dry weight per plant:

Nakano and Morita (2009) found that dry weight of plant at anthesis was not affected significantly by plant densities × nitrogen rate interactions.

D) Yield and yield components:

1- Number of spikes per square meter:

Number of spikes per square meter was not affected significantly by plant density (255 to 450 kernels m^{-2}) × nitrogen rate (0 to 25 kg N fad^{-1}) interactions in both seasons as found from **Spaner *et al*. (2000)**. **Nakano and Morita (2009)** observed that number of spikes per square meter was not affected significantly by plant densities × nitrogen rate interactions. Highest number of spikes per square meter could be produced at either plant density of 350 or 400 kernels m^{-2} with 25 kg N fad^{-1}, as infered from **Somarin *et al*. (2010)**.

2- Number of kernels per spike:

Spaner *et al*. (2000) found that number of kernels per spike was not affected significantly by plant densities × nitrogen rate interactions in both seasons. **Nakano and Morita (2009)** observed that number of kernels per spike was not affected significantly by plant densities × nitrogen rate interactions.

3- Thousand kernel weight:

Spaner *et al*. (2000) found that thousand kernel weight was not affected significantly by plant densities × nitrogen rate interactions in both seasons. Similarly, **Nakano and Morita (2009)** found that thousand kernel weight was not affected significantly by plant densities × nitrogen rate interactions. Maximum thousand kernel weight could be produced at either plant density of 350 or 400 kernels m^{-2} with 25 kg N fad^{-1}, as infered from **Somarin *et al*. (2010)**.

4- Grain yield per faddan:

Data of **Griffin (1998)** showed that grain yield for wheat was affected significantly by plant density (220 and 435 plants m^{-2}) × nitrogen rates (approximately 0 and 85 kg N fad^{-1}). Maximum grain yield was achieved at all possible treatment combinations except for higher plant density with more nitrogen treatment, which yielded less than other treatments by averaged 7.7 % due to higher lodging. In another experiment by them, grain yield for wheat affected significantly by plant density (386 and 242 plants m^{-2}) × nitrogen rates (approximately 0 and 150 kg N fad^{-1}). Highest yield was found to be achieved at lower plant density with less nitrogen rate, which yielded more than higher densities with more nitrogen treatment by 14 %. The reduction in the last treatment was due to lodging.

Spaner *et al*. (2000) found that grain yield was not affected significantly by plant densities × nitrogen rate interactions in both seasons. **Anderson *et al*. (2004)** mentioned that the optimum plant population varied from 35 to 175 plants m^{-2}; depended strongly on the enivronmetal conditions and cultivar. They reported that the addition of nitrogen fertilizer rates as a variable in the regression tree analysis did not induce any changes for selecting the optimum plant population as well as grain yield in a sets of 32 experiments under different growth conditions. **Gao *et al*. (2009)** found that grain yield was not affected significantly by seeding rate × nitrogen rate (0, 50 and 100 kg N fad^{-1}, in the form of urea) interactions in three growing seasons. **Nakano and Morita (2009)** observed also that grain yield was not affected significantly by plant densities × nitrogen rate interactions. **Somarin *et al*. (2010)** recommended plant density of 400 kernels m^{-2} with 25 kg N fad^{-1} to achieve highest grain yield. Results of **Abd-El-Nasser and Balah (2011)** showed that economic grain yield could be achieved by using 60 kg N fad^{-1} (in the form of ammonium nitrate) with plant densities of either 250 or 400 kernels m^{-2}.

5- Straw yield per faddan:

Spaner *et al*. (2000) found that straw yield was not affected significantly by plant densities × nitrogen rate interactions in both seasons. Data of **Gao *et al*. (2009)** showed that straw yield was not affected significantly by plant density × nitrogen rate interactions in three growing seasons. Results of **Abd-El-Nasser and Balah (2011)** showed that economic straw yield could be produced by using 80 kg N fad^{-1} with plant density of 400 kernels m^{-2}.

6- Harvest index:

By inferring data from **Spaner *et al*. (2000)**, harvest index was not affected significantly by plant densities × nitrogen rate interactions in both seasons. Results of **Somarin *et al*. (2010)** showed that maximum harvest index could be produced at plant density of 300 kernels m^{-2} with 50 kg N fad^{-1}. By inspecting data of **Abd-El-Nasser and Balah (2011)**, maximum harvest index (43.4 %) could be obtained by using 80 kg N fad^{-1} with plant density of 400kernelsm^{-2}.

MATERIALS AND METHODS

Two field experiments were conducted separately at the Agricultural Research and Experimental Center, Faculty of Agriculture, Moshtohor, Kalubia, Benha University, Egypt, during 2015/2016 and 2016/2017 on a clay soil. Soil samples were taken from the surface (30cm depth) to determine mechanical and chemical properties of soil in both trails and seasons (Table 1). Before the onset of both of the field trials, the experimental area was received a 15.5 kg P_2O_5 fad^{-1} as calcium single super-phosphate, then ploughed to a depth of 0.25 m. The subplot size was 3.5-m × 3-m of fifteen 0.20-m rows in both trails. The preceding crop was carrot (*Daucus carota*) in both trails and seasons.

The first experiment:

1- Treatments and experimental design.

The experiments were conducted as a randomized complete block with a split plot design in three replicates. The subplots were hand-planted by five cultivars included Misr 2, Gemmeza 11, Shandaweel 1, Giza 171 and Sids 12 on 29 November in both seasons. The pedigree of parental bread wheat cultivars (Table 2) was collected from Hamada (2015) and CIMMYT (2017). Each cultivar was planted at a density of 450 kernels m^{-2} in dry soil followed by flood irrigation.

At the beginning of tillering stage (DC 20) (DC, decimal code according to Zadoks *et al*., 1974), main plots were sprayed with paclobutrazole [(2 RS, 3RS)-1-(4-chlorophenyl)-4-4-dimethyl-2(1,2,4-triazol-I-yl)-pentan-3-ol] at 0, 50 and 100 ppm fad^{-1}, and then repeated at the beginning of stem elongation (DC 30), thus plots were received totally 0, 100 and 200 ppm fad^{-1}.

2- Crop management practices.

Plants were sprayed by Atlantis (Mesosulfuron-methyl) at 1000 ml fad^{-1} using motorized backpack sprayer after three weeks from the first application of paclobutrazole, for control grass and broadleaf weed. Mineral nitrogen fertilizer was applied as urea (NH_2CONH_2) at a rate of 75 kg N fad^{-1} in three equal doses following the first, second and third watering. Plots were surface irrigated four times during both growing seasons.

3- Sampling procedure

After the 4th irrigation during anthesis stage, all susceptible plants were lodged at wind speed of averaged 10 m/s **(Cairo Weather, 2016, 2017)** during March, in both seasons. At mid flowering stage (DC 65), soil was dried after the 4th irrigation to the level which permits to walk on it carefully and take root samples without observing damage.

Ten whole plants with roots were sampled from each plot. Five plants per each of two rows from the central were removed together from the ground using a trowel to minimize damage to coronal roots. Coronal root system was separated with scissors away from each plant and kept in a plastic bag. Shoot fresh weight was recorded quickly after root separation to avoid moisture loss and then kept in a paper bag. Number of roots per plant, root plate spread and structural rooting depth were recorded. The maximum spread of the root plate was measured as the distance between the outermost edges of the structural roots as described by **Sparkes *et al.* (2008)**. Structural rooting depth (mm) was measured as the distance from the base of the root plate to the soil surface, identified as the point where the stem colour changed from white to green, as described by **Berry *et al*. (2000).** For crown root details, see Plate 1 (Appendix 1).

Five structural roots were sampled randomly of each plant and their length was recorded. Diameter of individual structural root was recorded. Structural root are identified as roots which have more than 0.5 mm diameter, at the beginning of grain filling as described by **Sparkes *et al*. (2008)**. It is defined also as the sections of roots surrounded by a rhizosheath **Berry *et al*. (2000)**. The rhizosheath is a dense mat of hairs that cover the upper sections of crown roots as identified by **Berry *et al*. (2004)**. These sections of roots have been shown to have an outer ring of lignified tissue in addition to the lignified central stele, which is why the rhizosheath is used to estimate the length of root that provides anchorage.

The coronal root system which had been removed from the plants was washed carefully to clean away soil residuals. Total coronal roots included the ten separated roots were oven dried at 75°C for 48 hours as described by **Traipathi *et al*. (2005)** to measure the root dry weight per plant. Shoots were allowed to air-dry in the laboratory for a ten days then oven dried at 70°C for 72 hours as described by **Chen *et al*. (2008)** to measure the shoot dry weight. Number of tillers per 0.7 m^{-2} and plant height were recorded also at mid flowering stage.

4- Lodging score determination

After the 4th irrigation, all susceptible plants were root lodged one time during mid-flowering stage (DC 65) and no stem lodging was observed for both seasons. To score lodging, firstly, angle of stem that lodged from vertical was measured in plots by angle meter application (Software that installed on Samsung Galaxy Mega Mobile GT-19152). Angle of lodged plants almost ranged from 76° to 78° in this trail, whereas upstraight stems without lodging have angle of 90°. Secondly, the percentage of plot that lodged was calculated. Finally, lodging for the plot or lodging score was calculated using Microsoft Excel program by the following formula: $[(\%\ \text{plot area lodged}) \times (\text{angel of lodging from the vertical})]/90$ as described by **Fischer and Stapper (1987)**. Lodging score has a range from 0 – 100 which 0 refers to no lodging, whereas 100 refers to the crop that completely flat.

5- Yield and yield components.

At physiological maturity (within 155 days after planting), twenty stems were sampled from each plot to determine plant, kernels per spike and the thousand kernel weight as described by **Chen *et al*. (2008)**. Plants in three adjacent rows from the central of each plot were sampled to determine number of spikes, grain and straw yield per 1.4 m^2 $plot^{-1}$, and values of harvest index were calculated. Spikes were threshed and kernels were separated then weighed. Grain yield was converted into kilograms per faddan.

6- Statistical analysis

Data were combined across two seasons and statistically analyzed by SPSS program (version, 23) using a general linear model (GLM) procedure. The least significant difference (LSD) test was used when mean difference were significant by SAS program (version, 6.12). Phenotypic correlations values (Pearson's correlation) were calculated between all plant characters at anthesis versus lodging score for combined data only. Simple and multiple linear regressions analysis were determined for combined data across 2016 and 2017 seasons between lodging score as a dependent variable with all shoot and root characters at anthesis, where each of them was considered as an independent variable.

The second experiment:

1- Treatments and experimental design.

The experiments were conducted as a randomized complete block with a split plot design in three replicates. The subplots were planted by hands by Giza 171 at three densities as 250, 350 and 450 kernels m^{-2} on 29 November in both seasons. Main plots were fertilized by mineral nitrogen fertilizer in the form of urea at rates of 0, 25, 50, 75 and 100 kg N fad^{-1} in three equal doses following the first, second and third watering. Crop management practices were conducted as well as in the first experiment and all following steps either. At anthesis, flag leaf samples were taken from ten plants of each plot to determine their area per square centimeter by the following formula (leaf length × maximum leaf width × constant of 0.75) as described by **Voldeng and Simpson (1967)**. Statistical analysis was done as well as in the first experiment, but neither Pearson's correlation nor regression analysis were made.

Table 1. Mechanical and chemical properties of the experimental soil before the onsets of the experiments at Moshtohor, across 2016 and 2017 seasons.

Soil properties	**First experiment**	**Second experiment**
Particle size distribution (Mechanical		
Course sand %	13.25	14.62
Silt %	43.63	41.26
Clay %	43.12	44.12
Texture grade %	Clay	Clay
Chemical analysis		
Electrical conductivity (E.C.)	1.66	1.48
pH (1 : 2.5)	7.81	7.52
$CaCO_3$ (%)	0.00	0.00
Organic matter (%)	1.95	1.85
Total N (%)	2.45	3.50
Available P (mg kg^{-1})	5.27	11.56
Available K (mg kg^{-1})	722.67	651.12
Available Ca (mmolc L^{-1})	6.60	5.50
Available Mg (mmolc L^{-1})	5.00	5.40
Available Na (mmolc L^{-1})	1.28	1.32
Available Cl (%)	7.00	6.40
Available HCO_3 (mmolc L^{-1})	2.80	3.00
Available SO_4 (mmolc L^{-1})	3.67	3.73

Table 2. The pedigree of parental bread wheat cultivars.

Cultivar	**Pedigree†**	**Year**
Misr 2	SUPER-KAUZ/BAVIACORA-92	2011
Gemmeza 11	Bow"s"/Kvz"s"//7c/seri82/3/Giza 168/Sakha61	2010
Giza 171	Gemmeza9/Sakha93	2015
Shandaweel 1	SITELLA/MOCHIS-73/4/NACOZARI-76/AG.IN,var.acutum//3*PAVON-76/3/MIRLO/BUCKBUCK	2013
Sids 12	BUCKBUCK//SIETE-CERROS-66/(ALD)ALONDRA/5/MAYA-74/OLESEN//1160.147/3/BLUEBIRD/GALLO/4/CHAT(SIB)/6/MAYA-74/VULTURE//CMH-74-A-63014/SUPER-X	2008

† The pedigrees for all cultivars were according to CIMMYT (2017) organization, except for Gemmeza11 which was according to Hamada (2015).

RESULTS AND DISCUSSION

The First Experiment

Generally, combined analysis (Tables 3, 4, 5) shows that neither year nor year interactions were significant for all traits of study.

I- <u>Effect of plant growth retardant (PGR):</u>

A) Lodging score:

Table (3) shows that root lodging score was not affected significantly by PGR application. This is in agreement with Tripathi *et al*. (2003) as they reported that PGR application was more related to stem-lodging resistance rather than root lodging resistance. However, lodging was reduced significantly by PGR treatments as found by (Humpfries, 1968; Knapp *et al*., 1987; Crook and Ennos, 1995; Griffin 1998; Berry *et al*., 2000; Berry *et al*., 2004; Tripathi *et al*., 2004; Ramburan and Greenfield, 2007; Sinniah *et al*., 2012).

B) Root characters:

All root characters were affected significantly by PGR tratments except for structural rooting depth, structural root length and diameter (Table 3).

1. Root plate spread:

The spread of the root plate was affected significantly ($P<0.05$) by PGR application. Root plate spread increased by 34.9 and 39.6 % at 100 and 200 ppm paclobutrazole, respectively, compared to untreated plants (Table 3**)**. Similarly, (Griffin, 1998) found a significant enlargement in the spread of the root plate, but (Crook and Ennos, 1995; Berry *et al*., 2000) found that PGR treatments did not affect the spread of the root plate**.**

2. Number of roots per plant:

Table (3) shows that number of roots per plant was affected significantly ($P<0.05$) by PGR application. Maximum root number per plant was higher by 36% at 200 ppm paclobutrazole when compared with untreated plants. The same trend was obtained by (Bragg *et al*., 1984; Crook and Ennos, 1995; Montfort *et al*., 1996). Treated plants by PGR at 100 ppm paclobutrazole did not differ significantly for the number of roots when compared with untreated plants (Table 3).

3. Structural rooting depth:

PGR application did not affect the structural rooting depth significantly (Table 3). In a like manner, Berry *et al*. (2000) reported that using PGR did not affect the structural rooting depth, while deepend roots caused by PGR treatments was reported by (Montfort *et al*., 1996; Griffin, 1998).

4. Structural root length:

Table (3) shows that structural root length was not differed significantly by PGR application. Rajala *et al*. (2002) observed the same results as they found that 3-PGRs did not change root length of wheat. On the other hand, PGR treatments doubled root length of wheat (Griffin, 1998); slightly increased root length of barley (Bragg *et al*., 1984); and it reduced root length of barley (Woodward and Marshall, 1987).

5. Root dry weight per plant:

Table (3) shows that root dry weight per plant at anthesis was differed significantly ($P<0.01$) by treated plants via PGR. Root dry weight per plant increased gradually by 15.7 and 24.1 % at 100 and 200 ppm paclobutrazole, respectively when compared with untreated plants. Likewise, (Humpfries, 1968; Bragg *et al.*, 1984) found increases in dry weight of roots by PGR treatments, while (Woodward and Marshall, 1987; Blouet *et al.*, 1991; Rajala and Peltonen-Sainio, 2001) noticed significant inhibition in root dry weight via PGR. In contrast with above results, Rajala and Peltonen-Sainio (2001) observed similar effect of whether 2-PGRs or control on root dries weight of spring wheat.

Paclobutrazole has been increased root growth and improved root to shoot ratio, as reported by (Berova and Zlatev, 2000). Increased root dry weight per plant in this study could be mainly due to investment more assimilates in root system due to shortened plant height by paclobutrazole application (Table 4). Consequently, the spread of the root plate was larger and more roots were produced per plant (Table 3).

Yet, favorable significant increases in roots' width, numbers and dry weight by PGR application still not enough to improve lodging resistance, this might indicate whether there are other root traits strongly affecting lodging behavior which was not affected positively by PGR application (i.e. root length or depth or diameter); or lodging behavior depending on all root traits collectively; and/or other morphological plant characteristics.

Table 3. Effects of PGR treatments and cultivars for lodging score and root characters of wheat in combine analyses across 2016 and 2017 seasons with related analysis of variance.

Main effect	Lodging score	Root plate spread	Roots plant^{-1}	Structural root depth	Structural root length	Structural root diameter	Root dry weight
		mm	no.	mm	mm	mm	g plant^{-1}
Paclobutrazole (ppm)							
0	27.55	21.27	9.93	35.73	120.67	8.07	0.296
100	26.86	32.67	13.87	35.53	122.07	13.67	0.351
200	26.39	35.20	15.53	38.13	123.13	16.27	0.390
LSD (0.05)	NS	7.88	4.06	NS	NS	NS	0.019
Cultivar							
Misr 2	0.00	35.00	15.00	39.78	136.78	15.00	0.401
Gemmeza 11	0.00	39.56	20.00	43.33	159.56	18.78	0.427
Shandaweel l	0.00	30.89	14.56	37.78	125.22	14.11	0.367
Giza 171	64.36	21.67	8.22	31.33	97.67	8.44	0.270
Sids 12	70.29	21.44	7.78	30.11	90.56	7.00	0.264
LSD (0.05)	9.87	8.94	3.66	6.11	14.52	4.13	0.037
				Significance			
Year (Y)	NS	NS	NS	NS	NS	NS	NS
Rep (year)	NS	NS	NS	NS	NS	NS	NS
Paclobutrazole (PGR)	NS	*	*	NS	NS	NS	**
Y × PGR	NS	NS	NS	NS	NS	NS	NS
Cultivar (C)	**	**	**	**	**	**	**
Y × C	NS	NS	NS	NS	NS	NS	NS
PGR × C	NS	NS	NS	NS	NS	**	NS
Y × PGR × C	NS	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

C) Growth:

1. Plant height:

Table (4) shows that plant height was significantly ($P<0.05$) affected by PGR application. Treated plants by paclobutrazole at 100 and 200 ppm reduced plant height by 15.1 and 23.8 %, respectively, than untreated plants. These results were similar to those obtained by (Humphries *et al*., 1965; Lowe and Carter, 1972; Knapp *et al*., 1987; Crook and Ennos, 1995; Flintham *et al*., 1997; Griffin, 1998; Berry *et al*., 2000; Alam *et al*., 2002; Rajala and Peltonen-Sainio, 2002; Tripathi *et al*., 2003, 2004; Berry *et al*., 2004; Ramburan and Greenfield, 2007; Shekoofa and Emam, 2008; Sinniah *et al*., 2012). Paclobutrazole is a plant growth retardant that acts by inhibiting activity of *ent*-kaurene oxidase, which catalyses the sequential oxidation of kaurene to *ent* kaurenoic acid in the early step of the biosynthetic pathway of Gibberellic acid (GA3), resulting in retardation of internodes, reduction in culm length and reduction in total plant height (Sinniah *et al*., 2012).

2. Number of tillers per square meter:

Table (4) showed that number of tillers per sqaure meter at anthesis was affected singnificantly ($P<0.05$) by PGR treatments. Treated plants by paclobutrazole at 100 and 200 ppm increased tillers per square meter by 12.7 and 15.8 %, respectively, than untreated plants (Table 4). These results were coincided with those observed by (Humpfries, 1968; Rajala and Peltonen-Sainio, 2001; Alam *et al*., 2002; Tripathi *et al*., 2003; Berry *et al*., 2004; Shekoofa and Emam, 2008) but were not observed by Griffin (1998) as he found significant decreased for number of tillers by PGR application. Increased tillering capacity by paclobutrazole in this study was matched with the reduction in plant height, thus more assimilates could be partitioned to produce more tillers per plant.

3. Shoot fresh weight per plant:

Table (4) shows that shoot fresh weight per plant at anthesis was differed significantly (P<0.01) by PGR application. Treated plants by paclobutrazole at 100 and 200 ppm increased shoot fresh weight per plant at anthesis by 15.7 and 18.1 %, respectively, than untreated plants**.** However, Crook and Ennos (1995) found that PGR application significantly reduced stem and spike fresh weights at grain filling.

4. Shoot dry weight per plant:

Table (4) shows that shoot dry weight per plant at anthesis was varied significantly (P<0.05) by PGR treatments. Treated plants by paclobutrazole at 100 and 200 ppm increased shoot dry weight per plant at anthesis by 14.6 and 17.4 %, respectively, than untreated plants**.** However, Crook and Ennos (1995) found that PGR application significantly reduced stem and spike fresh weights at grain filling. These results were matched with Shekoofa and Emam (2008) as they indicated significant increase in shoot dry weight per plant by PGRs than untreated plants. Conversely, Rajala and Peltonen-Sainio (2001) reported significant reduction in shoot dry weight per plant when treated by PGRs. In contrast with above results, Tripathi *et al*. (2004) revealed that dry weight of plants was not affected by PGR in the first season while it was increased by only 3.5 % in the second.

Since plant height was decreased by paclobutrazole in this study, more assimilates were partitioned to produce more tillers per plant which were resulted in increased shoot dry weight at anthesis. In addition, paclobutrazole has been found to enhance the chloroplast synthesis that is responsible mainly for producing the dry matter (Berova and Zlatev, 2000).

Yet, PGR application made favorable modifications in shoot characters (reduced plant height or produced numerous and heavy tillers), but lodging score was not, consequently this may indicate that these alternations were not at the proper level and/or, some specific root characters were the key factors for lodging resistant., i.e. root length or depth or diameter.

Table 4. Effects of PGR treatments and cultivars for shoot characters of wheat at anthesis in combine analyses across 2016 and 2017 seasons with related analysis of variance.

Main effect	Plant height	Tillers m^{-2}	Shoot fresh weight	Shoot dry weight
	cm	no.	g $plant^{-1}$	g $plant^{-1}$
Paclobutrazole (ppm)				
0	117.53	519.73	10.78	6.84
100	99.73	595.13	12.79	8.01
200	89.60	617.20	13.17	8.28
LSD (0.05)	13.74	70.85	0.88	0.806
Cultivar				
Misr 2	107.33	642.67	13.15	8.30
Gemmeza 11	108.00	677.89	13.78	8.60
Shandaweel l	106.89	610.33	12.11	7.60
Giza 171	86.67	484.56	11.25	7.04
Sids 12	102.56	471.33	10.94	7.01
LSD (0.05)	9.07	59.12	0.57	0.671
		Significance		
Year (Y)	NS	NS	NS	NS
Rep (year)	NS	NS	NS	NS
Paclobutrazole (PGR)	*	*	**	*
Y × PGR	NS	NS	NS	NS
Cultivar (C)	**	**	**	**
Y × C	NS	NS	NS	NS
PGR × C	NS	NS	NS	NS
Y × PGR × C	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

D) Yield and yield components:

1- Number of spikes per square meter at harvest:

PGR application exhibited significant ($P<0.05$) impact on the number of spikes per square meter at harvest stage (Table 5). Treated plants by paclobutrazole at 200 ppm increased spikes per square meter by 17.8 % than untreated plants. Increased spikes by PGR application observed also by (Humphries *et al*., 1965; Humphries and Bond, 1969; Berry *et al*., 2004); Ramburan and Greenfield (2007) in the first location; and also by Shekoofa and Emam (2008). However, no differences in spikes number via PGRs were observed as found by (Lowe and Carter (1972; Rajala and Peltonen-Sainio, 2002; Tripathi *et al*., 2004); and Ramburan and Greenfield (2007) in the second location. Number of spikes at 100 ppm paclobutazole did not change significantly than at 200 ppm or control (Table 5). In a like manner, Sinniah *et al*. (2012) found that treated rice plants by Paclobutrazole at either 0 or 100 ppm had no significant impact on the number of panicles per unit area.

Number of tillers had increased by paclobutrazole in this study at denser canopy of 450 kernels m^{-2} (Table 4). Consequently, shading by plants was at the maximum level, and this could be tended plants to produce more spikes per unit area. In a like manner, UIIah (2014) reported that denser canopies have enhanced the fertility of tillers.

2- Number of kernels per spike:

PGR application exhibited significant ($P<0.05$) impact on the number of kernels per spike (Table 5). Treated plants by paclobutrazole at 200 ppm decreased kernels number per spike by 12.7% than untreated plants. Under lodging conditions, Berry *et al*. (2004) and Tripathi *et al*. (2004) observed also reduction in kernels number per spike via PGR application, while

(Humphries and Bond, 1969; Sinniah *et al.*, 2012) found significant increasing than control. However, no differences in kernels number per spike via PGRs were observed as obtained by (Humphries *et al.*, 1965; Lowe and Carter, 1972; Rajala and Peltonen-Sainio, 2002; Ramburan and Greenfield, 2007; Shekoofa and Emam, 2008). Table (5) shows that number of kernels per spike at 100 ppm paclobutazole did not change significantly than control (Table 5). In contrast, Sinniah *et al*. (2012) observed that treated plants by paclobutrazole at 100 ppm significantly increased number of kernels per panicle than control.

The reduction in kernels per spike by paclobutrazole in this study, could be due either the negative impact of paclobutrazole on spike length which may reduced or by increasing number of spikes for treated plants via paclobutrazloe. It is well known that there is a large compensation among yield components such as number of spikes per unit area, kernels number and kernel weight. Therefore, as the number of spikes was increased in this study, the number of kernels was dropped while thousand kernel weight did not change (Table 5).

3- Thousand kernel weight:

Thousand kernel weight was not affected significantly by PGR application (Table 5). These results were in confirmation with those by (Humphries *et al*., 1965; Lowe and Carter, 1972; Tripathi *et al*., 2004; Ramburan and Greenfield, 2007). Nevertheless, (Humphries and Bond, 1969; Griffin, 1998; Rajala and Peltonen-Sainio, 2002; Berry *et al*., 2004;) found reduction in kernels weight by PGR application, whereas increasing in kernnels weight were noticed by Shekoofa and Emam (2008). Similarly, Sinniah *et al*. (2012) found increasing in kernels weight of rice at 100 ppm paclobutrazole while at 200 ppm, the weight did not differ than control.

4- Grain yield per faddan:

Grain yield was not affected significantly by PGR application (Table 5). These results were consistent with those by (Humphries *et al*., 1965; Lowe and Carter, 1972; Griffin, 1998; Berry *et al*., 2000; Ramburan and Greenfield, 2007; Brinkman *et al*., 2012). However, Alam *et al*. (2002) found reduction in grain yield at 10 or 30 ppm ethephon. Similar reductions were observed by Rajala and Peltonen-Sainio, (2002) and Tripathi *et al*. (2004). On the other hand, increasing in grain yield via PGRs was found by (Humphries and Bond, 1969; Knapp *et al*., 1987; Shekoofa and Emam, 2008). Similar increases were observed also by Alam *et al*. (2002) when they treated plants by ethephon at 20 ppm. In a like manner, Sinniah *et al*. (2012) mentioned that application of paclobutrazol increased rice grain yield directly by 8% and indirectly through decreases in losses of up to 20% due to lodging. Their data also showed that grain yield of treated rice by Paclobutrazole at 100 ppm had exceeded those which were achieved at 200 ppm by 6 %. Berry *et al*. (2004) reported that PGR applications could either increase yield by zero to less than 15 % or reduced the grain yield as much as 50%.

PGR applications slightly improved grain yield by insignificant 5.6 % in this study (Table 5). PGR treatments enhanced both of the tillers generative capacity by plants and the fertility of these tillers, which resulted in more spikes m^{-2}. However, PGR applications reduced kernels $spike^{-1}$, but did not affect kernels weight. Therefore, the insignificant increase in grain yield by PGR was mainly due to the increase in the number of spikes per square meter.

5- Straw yield per faddan:

Table (5) shows that straw yield was affected significantly ($P<0.05$) by PGR treatments. Treated plants by paclobutrazole at 100 or 200 ppm, increased straw yield by 7.2 and 10.7% than untreated plants. Straw yield at 100 ppm paclobutrazole did not differ significantly than at 200 ppm (Table 5). Straw yield increases were observed by Alam *et al*. (2002) when they treated plants by ethephon at 10 or 20 ppm. Increasing in straw yield by PGR application was found also by Tripathi *et al*. (2004) but was not by Griffin (1998) as he found a reduction in straw yield. In contrast with above results, straw yield did not differ as observed by Alam *et al*. (2002) when they treated plants by ethephon at 30 ppm. Shekoofa and Emam (2008) found also no differences between treated and untreated plants by PGRs. Vegetative structures of plants were responded positively by PGR treatments in this study, which could be resulted in more straw yield.

6- Harvest index:

Table (5) shows that harvest index was not affected significantly by PGR treatments. This was in agreement with Alam *et al*. (2002) when they treated plants by ethephon at 20 ppm but at 10 or 30 ppm, they found significant reduction in harvest index values. Such reduces were observed also by Tripathi *et al*. (2004). However, Griffin (1998) and Shekoofa and Emam (2008) found increases in harvest index by PGRs.

Table 5. Effects of PGR treatments and cultivars for wheat yield and its components in combine analyses across 2016 and 2017 season with related analysis of variance.

Main effect	Spikes m^{-2}	Kernels Spike^{-1}	Thousand kernel wt.	Grain yield	Straw yield	Harvest index
	——— no. ——		g	——— kg fad^{-1} ———		%
Paclobutrazole (ppm)						
0	434.00	31.63	37.78	2847.13	3304	46.29
100	499.13	27.91	40.31	2996.67	3563	45.68
200	527.87	27.61	45.55	3037.20	3703	45.06
LSD (0.05)	71.75	4.01	NS	NS	213	NS
Cultivar						
Misr 2	489.22	26.39	44.20	3169	3687	46.56
Gemmeza 11	499.44	28.39	44.00	3091	3987	43.89
Shandaweel l	493.00	29.44	43.67	2980	3650	46.54
Giza 171	483.33	27.32	37.10	2789	3498	44.73
Sids 12	470.00	27.23	37.10	2773	3392	45.75
LSD (0.05)	NS	NS	6.21	189	NS	NS
			Significance			
Year (Y)	NS	NS	NS	NS	NS	NS
Rep (year)	NS	NS	NS	NS	NS	NS
Paclobutrazole (PGR)	*	*	NS	NS	*	NS
Y × PGR	NS	NS	NS	NS	NS	NS
Cultivar (C)	NS	NS	*	**	NS	NS
Y × C	NS	NS	NS	NS	NS	NS
PGR × C	NS	NS	NS	NS	NS	NS
Y × PGR × C	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

II- Effect of cultivar:

A) Lodging score:

Table (3) shows that lodging score was affected significantly by cultivars (P<0.01). Sids12 and Giza171 recorded the highest lodging scores which were 70 and 64, respectively, while Misr2, Gemmeza11 and Shandaweel1 recorded all zero scores. Varietal differences in lodging score from 0 to 100 were observed also in studies by (Knapp *et al*., 1987; Stapper and Fischer, 1990; Easson *et al*., 1993; Crook and Ennos, 1994; Crook and Ennos, 1995; Griffin, 1998; Spink *et al*., 2003; Tripathi *et al*., 2003, 2004, 2005; Ramburan and Greenfield, 2007; Brinkman, 2012).

B) Root characters:

Generally, Table (3) shows that three resistant cultivars group (Misr2, Gemmeza11 and Shandaweel1) recorded averagely highest values of root characters when compared with the two susceptible cultivars group (Sids12 and Giza171). Although resistant cultivars behaved similar lodging resistance, but there were significant variability among them in all root characters except for root plate spread and structural root depth. Susceptible cultivars group behaved almost similar lodging behavior and there were no significant variation between them in all root characters.

1- Root plate spread:

Table (3) shows that the spread of the root plate was varied significantly (P<0.01) among cultivars. Resistant cultivars group produced wider roots than susceptible cultivars group by average 38.7 % due to the genotypic differences. Similarly, (Griffin, 1998; Berry *et al*., 2000; Spink *et al*., 2003 Berry *et al*., 2007; Sparkes *et al*., 2008; Pinera-Chavez *et al*., 2016) strongly suggested that genotypes should have wider root plate for achieving root lodging resistance for wheat. However, resistant and susceptiple varieties produced the same width of the root plate as inferred from Crook and Ennos (1993, 1994, 1995). In addition, resist cultivar was less than 2 out of 3 susceptible cultivars by averaged 9.3 % as detected from Crook and Ennos (1994).

2- Number of roots per plant:

Table (3) shows that number of roots per plant was varied significantly ($P<0.01$) among cultivars. Resistant cultivars group produced more roots than susceptible cultivars group by average 50.6 % due to the genotypic differences. Similarly, resistant cultivars produced more roots per plant as observed in studies by (Griffin, 1998; Crook and Ennos, 1993, 1995). Moreover, Crook and Ennos (1995) concluded that stronger root system had depended on the number of roots per plant rather than some other traits in root system. They reported also that Galahad had weaker anchorage system due to the smaller number of roots per plant when compared with resistant Hereward. Moreover, Crook and Ennos (1994) found that the resist cultivar produced roots less than 1 out of 3 susceptible cultivars by insignificant 6.3 %, while exeeded the other 2-susceptible cultivars by 13 %. Although resistant cultivars behaved similar lodging resistance in our study, but there were significant variability among them in the number of roots per plant. Gemmeza11 produced more roots than Misr2 and Shandaweel1 by 25 and 27.2 %, respectively (Table 3). These differences could be due to the genotypic differences.

3- Structural rooting depth:

Table (3) shows that structural rooting depth per plant was differed significantly among cultivars. Resistant cultivars group produced deeper roots than susceptible cultivars group by average 23.8 % due to the genotypic differences. In a like manner, lodging susceptibility differed between varieties and deeper roots was responsebile for lodging resistance in many studies as by (Griffin, 1998; Spink *et al*., 2003; Berry *et al*., 2007; Thorup-Kristensen, 2009).

4- Structural root length:

Table (3) shows that structural root length was differed significantly (P<0.01) among cultivars. Resistant cultivars group produced taller roots than susceptible cultivars group by average 33 % due to the genotypic differences. Further, Griffin (1998) and Berry *et al*. (2007) observed varietal differences among cultivars for the root length. Crook and Ennos (1994) found the resist cultivar produced shorter roots than 2 out of 3 susceptible cultivars, while exeeded the last by 10.4 %. In a like manner, the structural root length for the resist cultivar was shorter than the susceptible one by 8.9 % as inspected from Crook and Ennos (1993). Although resistant cultivars behaved similar lodging resistance in our study, but there were significant variability among them in root length. Gemmeza11 produced taller roots than Misr2 and Shandaweel1 by 14.3 and 21.5 %, respectively (Table 3). These differences could be due to the genotypic differences.

5- Structural root diameter:

Table (3) shows that structural root diameter was differed significantly (P<0.01) among cultivars. Resistant cultivars group produced thicker roots than susceptible cultivars group by average 51.6 % due to the genotypic differences. Spink *et al*. (2003) noticed that thicker roots was responsebile for lodging resistance. Berry *et al*. (2007) detected variation in root diameter between varieties. Pinera-Chavez *et al*., 2016) mentioned that spring wheat has thinner roots than winter wheat. Although resistant cultivars behaved similar lodging resistance in our study, but there were significant variability among them in root diameter. Gemmeza11 produced thicker roots than Shandaweel1 by 24.9 %, whereas Misr2 did not differ significantly for the both ones (Table 3). These differences could be due to the genotypic differences.

6- Root dry weight per plant:

Table (3) shows that root dry weight at anthesis was differed significantly (P<0.01) among cultivars. Resistant cultivars group produced heavier roots than susceptible cultivars group by average 33 % due to the genotypic differences. **Berry *et al*. (2007)** and **Pinera-Chavez *et al*. (2016)** found a strong relationship between root dry weight and anchorage strength or root-lodging resistance in wheat. **Evans *et al*. (1975)** reported also varietal differences in root weight between spring and winter wheat. Although resistant cultivars behaved similar lodging resistance in our study, but there were significant variability among them in root diameter. Gemmeza11 produced thicker roots than Shandaweel1 by 14.1 %, whereas Misr2 did not differ significantly for the both ones (Table 3). These differences could be due to the genotypic differences.

C) Growth:

1- Plant height:

Table (4) shows that plant height at anthesis was differed significantly ($P<0.01$) among cultivars. Cultivars, in the present study, were semi-dwarf and had almost similar height (averaged 106 cm) except for Giza171, which was significantly less than other cultivars by average 18.4%. Although susceptible cultivars of Sids12 and Giza171 were exhibiting similar lodging behavior in this study but they exhibited different height. Plant height for Giza171 was significantly less than Sids12 by 15.5% (Table 4). However, taller plants were tended to lodge in several studies as observed by (Knapp *et al*., 1987; Stapper and Fischer, 1990; Easson *et al*., 1993; Crook and Ennos, 1994; Berry *et al*., 2000; Navabi *et al*. (2006; Berry *et al*., 2007). On contrary, taller plants were not tended to lodge as found by Crook and Ennos (1995). In contrast with above results, (Crook *et al*., 1994; White *et al*., 2003; Tripathi *et al*., 2003, 2004, 2005; Ramburan and Greenfield, 2007) found no relationship between lodging and plant height.

The differences between Gemmeza11, Misr2, Shandaweel1 and Sids12 were less than 6 cm (Table 4). Similarly, Mehasen *et al*. (2015) found that the differences between Gemmeza11, Misr2 and Sids12 were in the range of 3.5 cm. likewise, the difference between Gemmeza11 and Sids12 was only 6 cm as inferred from Sidi (2015). Regardless of the lodging behavior, many studies found variation between cultivars for plant height (Abdallah *et al*., 2013; Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2014).

2- Number of tillers per square meter:

Table (4) shows that number of tillers per square meter at anthesis was differed significantly (P<0.01) among cultivars. Resistant cultivars group produced more tillers than susceptible cultivars group by average 25.7 % due to the genotypic differences. These results were in agreement with those by (Pinthus, 1973; Easson *et al*., 1993) and were not by (Hanley *et al*., 1961; Berry *et al*., 2000; Tripathi *et al*., 2003;) as they mentioned that more tillers increased lodging. In contrast with previous results, Crook and Ennos (1994, 1995) found similar number of tillers for both lodging resist and susceptible cultivars.

Table (4) shows that, within resistant cultivars group, Gemmeza11 produced more tillers than Shandaweel1 by 10 %, whereas Misr2 did not differ significantly for the both ones (Table 4). The two susceptible cultivars produced similar tillers with average 478 tiller (Table 4). However, Sids12 produced more tillers than Gemmeza11 by 4.2 % as inferred from Sidi (2015). In the absence of lodging, many studies found variations between cultivars for the number of tillers per sqaure meter (El-Gizawy, 2005; Abdel-Ati and Zaki, 2006; Gomaa *et al*., 2011; Abdallah *et al*., 2013).

3- Shoot fresh weight per plant:

Table (4) shows that shoot fresh weight at anthesis was differed significantly (P<0.01) among cultivars. Resistant cultivars group produced heavier plants than susceptible cultivars group by average 14.7 % due to the genotypic differences. These results were inconsistent with those by (Easson *et al*., 1993; Crook *et al*., 1994; Crook and Ennos, 1995) as they found that heavier plants were lodged more than lighter plants. On the other side, similar shoot fresh weights for both lodged and unlodged plants were inspected from Crook and Ennos (1994).

Table (4) shows that, within resistant cultivars group, shoot fresh weight for Gemmeza11 was significantly heavier than Misr2 and Shandaweel1 by 4.6 and 12.1 %, respectively. Both of susceptible cultivars produced similar fresh weight with average 11.1 g plant^{-1} (Table 4). Further variations for shoot fresh weight between cultivars were observed by Abdel-Ati and Zaki (2006).

4- Shoot dry weight per plant:

Table (4) shows that shoot dry weight at anthesis was varied significantly ($P<0.01$) among cultivars. Resistant cultivars group produced heavier plants than susceptible cultivars group by average 14 % due to the genotypic differences. These results were consistent with those by (Easson *et al*., 1993) and were not by (Crook and Ennos, 1994; Stapper and Fischer, 1990; Tripathi *et al*, 2003, 2004, 2005) as they found that heavier plants were lodged more than lighter plants.

Table (4) shows that, within resistant cultivars group, shoot dry weight for Shandaweel1 was significantly lighter than Gemmeza11 and Misr2 and by 11.6 and 8.4 %, respectively, while dry weight of the shoot did not differ significantly between the last cultivars. Both of susceptible cultivars produced similar dry weight of shoot with average 7 g plant^{-1} (Table 4). Further variations for shoot dry weight between cultivars were observed by (Abdel-Ati and Zaki, 2006; Gomaa *et al*., 2011; El-Metwally *et al*., 2012; Harb *et al*., 2012).

D) Yield and yield components:

1- Number of spikes per square meter at harvest:

Table (5) shows that number of spikes per square meter at harvest was not differed significantly ($P<0.01$) among cultivars, with averaged 487 spikes m^{-2}. Likewise, Abdel-Ati and Zaki (2006) found that cultivars showed non-significane impact on spikes per square meter. Similarly, the number of spikes per square meter was approximately 230 spike m^{-2} for each of Gemmeza11, Shandaweel1 and Sids12 as infered from Thanaa and El-Hussin (2013). In a like manner, the differences among Misr2, Gemmeza11 and Sids12 for the number of spikes per square meter were less than 22 spikes as detected from Mehasen *et al*. (2015). Likewise, the differences between Gemmeza11 and Sids12 for the number of spikes per square meter were less than 13 spikes as detected from Sidi (2015).

On the other hand, (Easson *et al*., 1993) observed more spikes by resistant cultivars, while (Tripathi *et al*., 2004, 2005; Ramburan and Greenfield, 2007) found that lodging resistant cultivars were associated with fewer spikes. Moreover, regardless of lodging behavior, many studies found variations between cultivars for the number of spikes per sqaure meter, as those by (Noureldin *et al*., 2013; Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2014).

Although resistant cultivars group produced more tillers than susceptible cultivars group by average 25.7 % (Table 4) under the same plant density, but similar number of spikes for the two groups could be produced due to enhancing the fertility of tillers at the last group rather than tillers generative capacity by plants, and vice versa for the first group.

2- Number of kernels per spike:

Table (5) shows that number of kernels per spike was not differed significantly among cultivars. These results were coincided with Easson *et al*. (1993) and the results of 1 out of 4 trials by Stapper and Fischer (1990). However, Stapper and Fischer (1990) observed that the lowest lodged genotypes could have less or more kernels than the highest lodged genotypes in the other 3 trials. On the other hand, the lowest lodged genotypes have more kernels per spike than the highest lodged genotypes as obsereved by Tripathi *et al*. (2005) and Ramburan and Greenfield (2007). Fischer and Stapper (1987) reported that kernels per spike were reduced significantly by lodging, which resulted in reduction, by 35 % in grain yield.

Number of kernels per spike was ranged from 27.23 to 29.44 kernels spike^{-1} without significant differences among cultivars (Table 5). These results were in confirmation with those by Thanaa and El-Hussin (2013). Nevertheless, Mehasen *et al*. (2015) found significant differences among Gemmeza11, Misr2 and Sids12 for the number of kernels per spike. Further, Sidi (2015) found significant differences among Gemmeza11 and Sids12 for the number of kernels per spike. Similarly, several studies reported variations between cultivars for the number of kernels per spike, as those by (Fateh and Abdel-Dayem, 2013; Noureldin *et al*., 2013; Seleem and Abd-Eldayem, 2013). However, Abdel-Ati and Zaki (2006) found that cultivars showed non-significane impact on the number of kernels per spike.

3- Thousand kernel weight:

Thousand kernel weight was differed significantly (P<0.01) among cultivars (Table 5). Heavier thousand kernel weights were observed at resistant cultivars group by average 15.6 % which is more than the two susceptible cultivars group (Table 5). The lowest-lodged genotype had often heavier kernels than highest-lodged genotypes as inferred from Stapper and Fischer (1990) with little exception. Likewise, unlodged plants produced heavier kernels than lodged plants as detected from (Fischer and Stapper, 1987; Easson *et al*., 1993; Berry *et al*., 2004; Tripathi *et al*., 2005). In contrast with previous results, thousand kernel weight for the susceptible variety was significantly higher than two lodging-resist varieties as inspected from Ramburan and Greenfield (2007).

Table (5) shows significant differences among cultivars for thousand kernel weight. Similarly, kernel weight differences among Gemmeza11, Sids12 and Shandaweel1 were less than 4.7 % as calculated from Thanaa and El-Hussin (2013). Moreover, kernel weight for Sids12 was lighter than Gemmeza11, Misr2 by 9.8 and 6.8 %, respectively, as inferred from Mehasen *et al*. (2015). Further, kernel weight for Sids12 was lighter than Gemmeza11 by 12.2 as inferred from Sidi (2015).

Within each of resistant and susceptible groups, there were not significant differences for the thousand kernel weight (Table 5). In the absence of lodging, Abou-Elela (2001) and Abdel-Ati and Zaki (2006) found also that thousand kernel weight was not affected among cultivars. Many studies have been observed variations among cultivars for the thousand kernel weight, as those by (Noureldin *et al*., 2013; Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2014; Alves *et al*., 2015).

4- Grain yield per faddan:

Grain yield was varied significantly ($P<0.01$) among cultivars (Table 5). Highest grain yield per faddan was achieved by resistant cultivars group by average 3080 kg fad^{-1}, and more than the two susceptible cultivars group by averaged 9.7 % (Table 5). These results were in confirmation with those by (Pumphrey and Rubenthaler, 1983; Fischer and Stapper, 1987; Knapp *et al*., 1987; Stapper and Fischer; 1990; Easson *et al*., 1993; Tripathi *et al*., 2004, 2005; Ramburan and Greenfield, 2007; Rajkumara, 2008; Pinera-Chavez *et al*., 2016). Our calculations showed that grain yield reductions for these previous studies were 23, 35, 6.1, 24.4, 51.3, 3.9, 35, 15, 66 and 80 %. Moreover, Berry *et al*. (2004) reported that the major reductions in grain yield occur when wheat lodged flat at anthesis or early on in grain filling stage, and losses could range from 31 to 80%.

Table (5) shows significant differences among cultivars for grain yield. In a like manner, grain yield of Gemmeza11 exceeded Shandaweel1 and Sids12 by 5.5 and 19.5 %, respectively, as calculated from Thanaa and El-Hussin (2013). Moreover, Gemmeza11 exceeded Misr2 and Sids12 by 3.4 and 8.5 %, respectively, as inferred from Mehasen *et al*. (2015). Further, Gemmeza11 exceeded Sids12 by 7.7 %, as inferred from Sidi (2015).

Within each of resistant and susceptible groups, there were not significant differences for grain yield (Table 5). The marginal differences within the resistant and susceptible cultivars group were not exceeding 6 and 0.6 %, respectively (Table 5). In the absence of lodging, many studies have been found variations between cultivars for grain yield, as those by (Abou-Elela, 2001; Geleta *et al*., 2002; Allam, 2005; El-Gizawy, 2005; Svecnjak *et al*., 2007; Stipesevic *et al*., 2009; Giambalvo *et al*., 2010; El-Metwally *et al*., 2012; Haile *et al*. 2012; Harb *et al*., 2012; Abou-Elnaga and El-Gharbawy, 2013; Abd-Elrazek and El-Sheshtawy, 2013; Abdallah *et al*., 2013; Fateh and Abdel-Dayem, 2013; Noureldin *et al*., 2013; Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2014). Nevertheless, Abdel-Ati and Zaki (2006) and Benin *et al*. (2012) found that grain yield was not affected among cultivars.

5- Straw yield per faddan:

Straw yield was not varied significantly among cultivars (Table 5). Similar results were inferred from Mehasen *et al*. (2015), as Gemmeza11 exceeded Misr2 and Sids12 by only 2.3 and 5 %, respectively. On the other hand, straw yield of Gemmeza11 exceeded Shandaweel1 and Sids12 by 18 and 19.5 %, respectively, as calculated from Thanaa and El-Hussin (2013). Moreover, Gemmeza11 exceeded Sids12 by 10.3 %, as inferred from Sidi (2015). In addition, regardless of lodging, many studies have been found variations among cultivars for straw yield, as those obtained by (Noureldin *et al*., 2013; Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2014). However, Abdel-Ati and Zaki (2006) found that straw yield was not affected among cultivars.

On the other side, Table (5) shows also that straw yield for resistant cultivars group exceeded the susceptible cultivars by insignificant 8.7 %. In a like manner, highest-lodged genotypes had always less straw yield than lowest-lodged genotypes by 5.8 to 24.9; 17.6 to 37.6; and 4 %, as inferred from studies by Stapper and Fischer (1990); Easson *et al*. (1993); and Tripathi *et al*. (2005), respectively.

6- Harvest index:

Harvest index was not differed significantly ($P<0.05$) among cultivars (Table 5), with average 45.5 %. Same results were inspected from Tripathi *et al*. (2005) as the harvest index values were identical for both lodging resistance and susceptible groups. Also, (Abou-Elela, 2001; Abdel-Ati and Zaki, 2006) found that straw yield was not affected among cultivars. Likewise, the harvest index of Sids12 was more than Gemmeza11 by only 1 %, as inferred from Sidi (2015). In contrast with above results, harvest index of Shandaweel1 significantly exceeded Gemmeza11 and Sids12 by 7.5 and 7.2 %, respectively, as calculated from Thanaa and El-Hussin (2013). Moreover, harvest index of Gemmeza11 and Misr2 significantly exceeded Sids12, as inferred from Mehasen *et al*. (2015).

On the other side, the highest-lodged genotypes have always less harvest index than lowest-lodged genotypes by 6 to 17; 11.2, as inferred from studies by Stapper and Fischer (1990); Easson *et al*. (1993). Genrally, regardless of lodging, many studies have been found variations among cultivars for harvest index, as those obtained by (El-Gizawy, 2005; Giambalvo *et al*., 2010; Harb *et al*., 2012; Abd-Elrazek and El-Sheshtawy, 2013; Abdallah *et al*., 2013; Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2014).

E) Phenotypic correlations:

Table (6) shows all possible phenotypic correlations among lodging score, root characters at anthesis, shoot growth at anthesis, yield and its components across 2016 and 2017 seasons. Generally, all traits of study were correlated negatively with lodging score ($P<0.01$) except for spikes per meter square, kernels per spike, straw yield and harvest index which were not correlated significantly with lodging score.

1- Lodging score versus all plant characters at anthesis.

Table (6) shows that all root characters such as root plate spread, roots plant^{-1}, structural root depth, structural root length, structural root diameter and root dry weight plant^{-1} were highly negative correlated with lodging score ($P<0.01$). The respective r-values for these traits were -0.54, -0.65, -0.63, -

0.75, -0.48 and -0.73. Favorable high means of these traits were accompanied with resistant cultivars as we indicated before and were essential for anchorage strength and root lodging resistance. These results were in agreement with those obtained by (Pinthus, 1973; Berry *et al.*, 2000; Pinera-Chavez *et al.*, 2016) as they mentioned that root width, numbers, diameters and weight have a close correlation with root lodging resistance.

Among all root characters, the maximum negative correlations ($P<0.01$) were for root length (-0.75) or root dry weight (-0.73) with lodging score, while r-value for the root plate spread with lodging score was -0.54, all at $P<0.01$(Table 6). Root length indicates whether root plate width and/or rooting depth are depending on the angle of root spread. Unfortunately, the angle of root spread was not included in this study. In a like manner, Berry *et al.* (2007) and Pinera-Chavez *et al.* (2016) strongly suggested more biomass in wheat roots for widening its root plate and increasing lodging resistance.

Root dry weight plant^{-1} may be considered as indicator to the ability of plant to producing new roots and/or producing taller roots and/or to partitioning more assimilates to root system which may influence the root diameter. Table (6) shows that among all root characters, the maximum positive correlation between root dry weight plant^{-1} was recorded with roots plant^{-1} ($r = 0.79$, $P<0.01$), while r-values were 0.67 with root diameter or 0.65 with root length. Therefore, heavy roots by cultivar in this study could be explained by roots number ($R^2 = 0.62$, $P<0.01$, from simple linear regression analyses) rather than diameter ($R^2 = 0.45$, $P<0.01$) or length ($R^2 = 0.42$, $P<0.01$). Similarly, Boatwright and Ferguson (1967) mentioned that root dry weight linearly correlated with roots number. However, Berry *et al.* (2007) indicated that the variation in root biomass was strongly correlated ($r = 0.91$)

with the root diameter but did not correlate with the total roots number or root length.

Table (6) shows that all root characters were correlated positively with tillers m^{-2} and r-values were ranged from 0.52 to 0.73 at $P<0.01$ (Table 6). Among all root characters, the maximum positive correlations were for root dry weight ($r=0.73$) with tillers m^{-2} ($P<0.01$), while r-values were 0.52 for either root spread or depth with tillers m^{-2} (Table 6). Boatwright and Ferguson (1967) mentioned that each tiller normally develops its own system of adventitious roots. Thus, increased root dry weight by producing more roots could be mainly due to producing more tillers per plant. Similarly, Pinthus (1973) suggested that greater tiller numbers may result in better developed root systems and less lodging. On contrary, Berry *et al*. (2000) found that produce more tillers $plant^{-1}$ increases root plate spread ($r = 0.65$ and 0.77 for 1994 and 1995 seasons, respectively) but could partially counteracted the root plate spread effect. Tripathi *et al*. (2003) coincided with Berry *et al*. (2000) as they found significant positive correlation between tillers m^{-2} at anthesis and lodging score, and did suggest that selection for lodging resistant cultivars depended on fewer tillers per plant.

Since all root characters in this study were correlated positively with tillers m^{-2}, thus, strong negative correlation for tillers m^{-2} with lodging score was also observed ($r = -0.70$, $P<0.01$). Therefore producing more tillers per plant could improve anchorage system by producing heavy roots, which could be related directly to producing more roots per plant. Consequently, our results were differed with those obtained by either Berry *et al*. (2000) or Tripathi *et al*. (2003).

More tillers also were correlated directly with heavy shoot fresh and dry weights at anthesis, r = 0.80 and 0.75, respectively at P<0.01 (Table 6). In this study, when root lodging occurs, shoot fresh weight plant^{-1} for all lodging resistant cultivars including Shandaweel1 were heavier than other two susceptible cultivars by 14.7 % (Table 4). Table (6) shows that each of shoot fresh and dry weight were negatively correlated with lodging score (r = -0.51 and -0.49, respectively at P<0.01). In contrast with these results, Stapper and Fischer (1990) found a positive correlation between lodging score and dry weight per square meter at anthesis. Similarly, (Easson *et al*., 1993; Crook *et al*., 1994; Crook and Ennos, 1995) recommended lighter stems for root lodging resistance as lighter weight reduces the forces that applied to plants by wind and gravity. However, Tripathi *et al*. (2003) found no correlation between lodging score and shoot dry weight.

Negative correlation for plant height with lodging score was observed in this study. However this correlation was at the moderate level as r-value was -0.31 at P<0.05 (Table 6). In addition, susceptible cultivars of Sids12 and Giza171 behaved similar lodging, but exhibited different heights as we indicated before (Table 4). Similar trend was observed by Tripathi *et al*. (2003, 2004, 2005) as they found no correlation between plant height and lodging score thus they countered the conventional believe that taller genotypes tended to lodge more than shorter ones. In contrast with above results, (Pinthus, 1973; Stapper and Fischer, 1990; Keller *et al*., 1999; Navabi *et al*., 2006) found significant positive correlation between plant height and lodging score. Moreover, Zuber *et al*. (1999) found positive correlation (r = 0.57, P<0.01) between plant height with lodging score for 15 spring wheat breeding lines.

2- Lodging score versus grain yield and its components:

In this study, most of spikes were already existed before lodging time which was occured after heading or within anthesis satge. Table (6) shows that there was no correlation between spikes m^{-2} with lodging score. However, Pinera-Chavez *et al*. (2016) mentioned that spike area for spring wheat greater than winter wheat because the absence of awns for winter wheat. Therefore, spring wheat will have a greater leverage and lodging than winter wheat for crops at the same height, yield and spikes m^{-2}.

Table (6) shows that there was no correlation between kernels spike^{-1} with lodging score. Pollination and fertilization processes in inflorescences may be completed at lodging time, thus the number of kernels per spike may not be affected by lodging. On the other hand, results of Easson *et al*. (1993) showed negative correlation ($r = -0.90$ and $R^2 = 81$ %, $P<0.05$) between the number of kernels per spike and lodging percentage.

In opposite to kernels spike^{-1}, thousand kernel weight was correlated negatively with lodging score ($r = -0.45$, $P<0.01$) (Table 6). Heavier thousand kernel weights were observed at resistant cultivars group by average 15.6 % more than the susceptible cultivars group. Since lodging time was before grain development stages in this study, therefore the translocation of assimilate processes from the source (i.e., leaves, stems and awns) to the sink (i.e., kernels) may be less efficient by lodged cultivars and leading to reduce grain weights compared with unlodged plants. Likewise, findings of Easson *et al*. (1993) showed negative correlation ($r = -0.78$ and $R^2 = 61$ %, $P<0.05$) between the thousand kernel weight and lodging percentage.

Negative correlation was observed between grain yield with lodging score ($r = -0.51$, $P<0.01$) (Table 6). Similarly, Easson *et al*. (1993) found negative correlation ($r = -0.88$ and $R^2 = 77$ %, $P<0.05$) between the grain yield and lodging percentage. Likewise, Navabi *et al*. (2006) found that grain yield was negatively correlated with lodging scores within 140 genotypes. However, Tripathi *et al*. (2004) found insignificant negative correlation between grain yield and lodging score due to late lodging occurrence.

Grain yield of the lodged cultivars group was less by 9.7 % than unlodged cultivars group (Table 5). Since the number of spikes m^{-2} and kernels $spike^{-1}$ were the same for lodged and unlodged group in this study, therefore grain yield loss could be mainly attribued to the the reduction in kernel weight by 15.5 % for lodged cultivars due to lodging ($r = -0.45$). Lodged plants may be negatively affecting the efficiency of translocation of assimilates from vegetative structures to the grains. Similarly, Berry *et al*. (2004) stated that the grain yield reductions could be as much as 50 % and were caused by decreases in kernel weight. Moreover, Fischer and Stapper (1987) mentioned that lodging after anthesis reduced crop growth rate, and the adverse effect of lodging on grain yield was ascribed to this reduction in photo-assimilate supply. They stated also that the crop in which lodging had least effect on grain yield was characterized by a reduced degree of source limitation during grain filling.

Table 6. Phenotypic correlations for lodging score, wheat growth and yield characters across 2016 and 2017 seasons.

	LS†	RPS	RP	SRD	SRL	SRDT	RDWP	HT	TILL	SFWP	SDWP	S	KS	TKW	GY	SY	HI
LS††	1.00																
RPS	-0.54	1.00															
RP	-0.65	0.57	1.00														
SRD	-0.63	0.39	0.62	1.00													
SRL	-0.75	0.57	0.68	0.52	1.00												
SRDT	-0.48	0.54	0.73	0.42	0.51	1.00											
RDWP	-0.73	0.63	0.79	0.64	0.65	0.67	1.00										
HT	**-0.31**	-0.20	-0.02	0.21	0.27	-0.15	-0.13	1.00									
TILL	-0.70	0.52	0.66	0.52	0.63	0.56	0.73	0.15	1.00								
SFWP	-0.51	0.50	0.60	0.60	0.52	0.49	0.73	-0.01	0.80	1.00							
SDWP	-0.49	0.47	0.52	0.54	0.45	0.50	0.63	0.00	0.75	0.89	1.00						
S	-0.11	0.19	0.24	0.14	0.09	0.28	0.29	-0.09	0.74	0.63	0.60	1.00					
KS	-0.07	**-0.37**	-0.27	-0.09	0.08	-0.39	-0.26	0.52	-0.10	-0.16	-0.16	-0.11	1.00				
TKW	-0.45	0.55	0.51	0.46	**0.35**	0.61	0.52	-0.18	0.22	0.29	0.38	-0.13	-0.66	1.00			
GY	-0.51	**0.34**	**0.36**	0.47	0.42	0.39	0.52	0.18	0.72	0.78	0.92	0.58	0.08	0.22	1.00		
SY	-0.20	0.43	0.41	0.07	0.26	**0.35**	0.39	**-0.37**	**0.37**	0.42	0.44	**0.33**	**-0.35**	0.26	0.26	1.00	
HI	-0.04	-0.25	-0.24	0.16	-0.11	-0.15	-0.13	0.40	-0.06	-0.10	-0.06	-0.08	**0.35**	-0.12	0.15	-0.90	1.00

†, †† LS: lodging score; SRD: RPS: root plate spread; RP: roots plant^{-1}; structural root depth; SRL: structural root length; SRDT: structural root diameter; RDWP: root dry weight plant^{-1}; HT: plant height; TILL: tillers m^{-2}; SFWP: shoot fresh weight plant^{-1}; SDWP: shoot dry weight plant^{-1}; S: spikes m^{-2}; KS: kernels spike^{-1}; TKW: thousand kernel weight; GY: grain yield; SY: straw yield; HI: harvest index, respectively.

Bolded-values indicate significant correlation at the 0.05 level (2-tailed).
Shaded-values indicate significant correlation at the 0.01 level (2-tailed).

F) Predicting lodging through plant characteristics:

Tables (7, 8) show all significant coefficient of determination (R^2) from simple and multiple regression analysis, between all plant characters at anthesis with lodging score across 2016 and 2017 seasons.

From the simple linear regression analysis, Table (7) shows that 10 traits at lodging time are explained individually from 10 % ($P<0.05$) to 56 % ($P<0.01$) of the total variation in lodging score. Around 50% of the total variation in lodging score was explained by either root length or root dry weight plant^{-1} or tillers m^{-2} ($P<0.01$). Since lodging is a complicated phenomenon that influenced by interaction between genotype with environmental factors (wind, rain, surface irrigation, soil) therefore, these three traits are explaining the total variation in lodging quite well in this study, while the other seven traits were not. Plant height explained the variation in lodging score by only 10 % at $P<0.05$ (Table 7). However, Stapper and Fischer (1990) mentioned that differences in height explained more than 80 % of the variation in lodging scores.

Regression analysis showed that root length was a key variable for explaining the variation in lodging score under the circumstances of this research. Table (7) shows that root length recorded the maximum R^2 value and explained the variation in lodging score by 56 % as shown from simple regression analysis. In addition, root length represented a constant in the best four (two-parameters) combinations in multiple regression analysis, where the R^2 values of root length with either roots plant^{-1} or structural rooting depth or tillers m^{-2} or root dry weight plant^{-1}, were 60, 64, 65 and 66%, respectively (Table 8).

When added root dry weight plant^{-1} or tillers m^{-2} or structural rooting depth separately to the model, which the root length was constant, a significant increase in R^2 was detected in the range of 8-10 % (Tables 7, 8), while it improved by only 2 % when added the spread of the root plate. Structural rooting depth was explained only 40 % of the total variation in lodging score, while root dry weight plant^{-1} or tillers m^{-2} explained 53 % and 49 %, respectively (Table 7). However, these three traits improved R^2 values in the same range (8-10%) when they added separately to the model that the root length was a constant. This means that the improvements for R^2 values when root depth added to the root length in the model, was greater than adding whether root dry weight or tillers m^{-2}. Consequently, these results may strongly indicate the unique role of root length and structural rooting depth together for explaining the variation in lodging score.

The spread of the root plate had explained only 29 % ($P<0.01$) of the total variation in lodging score, and much less than structural rooting depth (Table 7). Moreover, when added the spread of the root plate to the model, which the root length was constant, R^2 improved by only 2 % (Tables 7, 8) and much less than added rooting depth. Most of previous studies have suggested, mainly widen roots or more roots plant^{-1} in order to maximize root lodging resistance. However, at denser densities (450 kernels m^{-2}) in this study, unlodged plants produced more roots that extended vertically and horizontally to increase anchorage root-soil system, but it seemed that the extension of roots vertically was much more responsible for lodging resist rather than other root characters.

Tables (6, 7) shows that tillers m^{-2} are negatively correlated with lodging score ($r = -0.70$) and explained 49 % ($P<0.01$) of the total variation in lodging score. Therefore, more tillers m^{-2} could minimize root lodging in this study. Traipathi *et al*. (2003) also reported that the tillers m^{-2} at anthesis had explained the maximum (79%) of the variation in lodging score, but they found that the tillers m^{-2} were correlated positively ($r = 0.89$, $P < 0.01$) with lodging score and did suggest that selection for lodging resistant, cultivars should be having fewer tillers per unit area.

The results of multiple regression analysis showed that root length with roots plant^{-1} or tillers m^{-2} with roots plant^{-1}, had explained 60 and 57 %, respectively of the total variation in lodging score (Table 8). When roots plant^{-1} was added to the model which root length or tillers m^{-2} were a constants, R^{2} value was improved by 4 and 7 %, respectively (Tables 7, 8). Moreover, the maximum R^{2} was 66 % when the model includes root length and root dry weight together; as we indicated before that root weight could be explained by roots number ($R^2 = 0.62$) rather than other root characters, therefore this may indicate the slight role of roots number for lodging resistance. Similarly, Crook and Ennos (1995) concluded that stronger root system had depended on more roots per plant rather than other differences in root system. Since tillers m^{-2} was correlated positively with roots plant^{-1}, $r = 0.66$ at $P<0.01$ (Table 6), consequently, the beneficial effect of more tillers could be partially due to producing more roots per plant.

When tillers m^{-2} was constant in the model, added either root plate spread or roots plant^{-1} or root length or root dry weight plant^{-1} or structural rooting depth, had improved R^{2} by 5, 7, 7, 10 and 10%, respectively (Tables 7, 8). However, the effect of added structural root diameter or shoot fresh or shoot dry weight plant^{-1} was at very low level, where the improvement in R^{2} values did not exceed 1% (Table 8). These results may indicate that possible two-parameters combinations of tillers m^{-2} with all root characters (separately), except root diameter, explained the variation in lodging score fairly good (R^2, values were ranged from 54 to 59%), while adding the shoot weight did not.

Although shoot fresh and dry weight at anthesis were highly positive correlated with tillers m^{-2} (r = 0.80 and 0.75 at $P<0.01$) but their contribution to explain the variation in lodging score were individually at very low levels as 26 and 24 %, respectively (Table 7). In addition, their contribution for improving the R^2 values when constant of critical characters of either root length or tillers in multiple regression model, did not exceed 3% (Tables 7, 8). Therefore, more tillers m^{-2} increased shoot fresh and dry weight, and it seemed that the canopy protection against wind or lodging was due to the number of tillers per square meter rather than their weight. In other words, heavy or lighter plants at lodging had a similar impact on lodging resistance and fewer tillers could permit lodging due to their limited spread per unit area rather than their weight. Similarly, Tripathi *et al*. (2003) concluded that tillers m^{-2} had explained 79 % variation in lodging scores not the dry matter at anthesis. Their justification were depended on, that many genotypes which differed in lodging score, had the same dry matter at anthesis but differed largely in tillers m^{-2}. In addition, the results of correlation between lodging score and dry matter at anthesis were not significant and supported their idea. On the other hand, Stapper and Fischer (1990) found that dry weight at anthesis had explained 65 % of the variation in lodging with severe lodging risks for heaviest plants.

Best combinations of three characters included root length and root dry weight with structural rooting depth and they explained together 69 % of the total variation in lodging score (Table 8). However, R^2 improvements were in the range of only 3%. Consequently combination of three characters could be negligible to explain the variation in lodging score.

We concluded from previous results that canopy protection against lodging is related to both of plant aerial and underground parts that are work together in complementary way. This protection process by plants works via producing greatest number of tillers per unit area that are distributed and spread well against wind and/or higher values of most of root characters, in particularly, the root length and depth. Many researchers mentioned that shorter plants, lighter plants and fewer tillers with widen roots were essential for root lodging. However, in this study, these traits were not response so much to root lodging resistance. Under the circumstances of this research, limited ability for Giza171 and Sids12 at denser canopy to produce more tillers that accompanied with shorter root length and depth, leads to lodging and then negative impacts, in particular, reduction in kernels weight which resulted in grain yield loss when compared with unlodged cultivars such as Misr2, Gemmeza11 and Shandaweel1.

Table 7. Best significant coefficients of determination (R^2) from simple regression analysis between all root and shoot characters with lodging score (means across 2016 and 2017 seasons).

Parameters†	**R^2**
One character	
Structural root length	0.56**
Root dry weight plant^{-1}	0.53**
Tillers m^{-2}	0.49**
Roots plant^{-1}	0.42**
Structural rooting depth	0.40**
Root plate spread plant^{-1}	0.29**
Shoot fresh weight plant^{-1}	0.26**
Shoot dry weight plant^{-1}	0.24**
Structural root diameter	0.23**
Plant height	0.10*

† All parameters correlated negatively with lodging score.

*, ** Indicates significant at the 0.05, 0.01 levels, respectively.

Table 8. Best possible significant combinations of coefficients of determination (R^2) from multiple regression analysis between root, shoot characters with lodging score (means across 2016 and 2017 seasons).

Parameters†	**R^2**
Two characters	
Root length and root dry weight plant^{-1}	0.66**
Root length and tillers m^{-2}	0.65**
Root length and structural rooting depth	0.64**
Root length and roots plant^{-1}	0.60**
Root length and shoot dry weight plant^{-1}; or tillers m^{-2} with root dry weight plant^{-1} or structural rooting depth	0.59**
Root length with root plate spread plant or shoot fresh weight plant^{-1}	0.58**
Root length with plant height or structural root diameter	0.57**
Tillers m^{-2} and roots plant^{-1} or root length	0.56**
Tillers m^{-2} with root plate spread plant^{-1} or plant height	0.54**
Tillers m^{-2} with structural root diameter or shoot fresh weight plant^{-1} or shoot dry weight plant^{-1}	0.50**
Three characters	
Root length, root dry weight plant^{-1} and structural rooting depth	0.69**

† All parameters correlated negatively with lodging score.

** Indicates significant at the 0.01 level.

III- Effect of plant growth retardant and cultivar interactions:

Generally, PGRs × cultivar interactions were not significant for all traits of study except for the structural root diameter (Tables 3, 4 and 5).

A) Lodging score:

Table (3) shows that lodging score was not affected significantly by PGRs × cultivar interactions. Similar results were observed by (Ramburan and Greenfield, 2007; Sinniah *et al.*, 2012). However, (Crook and Ennos, 1995; Berry *et al.*, 2000; Berry *et al.*, 2004; Tripathi *et al.*, 2004) recommended PGRs for reducing lodging for different cultivars.

B) Root characters:

1- Root plate spread:

Table (3) shows that the spread of the root plate was not differed significantly by PGRs × cultivar interactions. These results were coincided with those observed by Crook and Ennos (1995).

2- Number of roots per plant:

PGRs × cultivar interactions exhibited non significant impact on root number per plant (Table 3). These results were matched with those obtained by Crook and Ennos (1995).

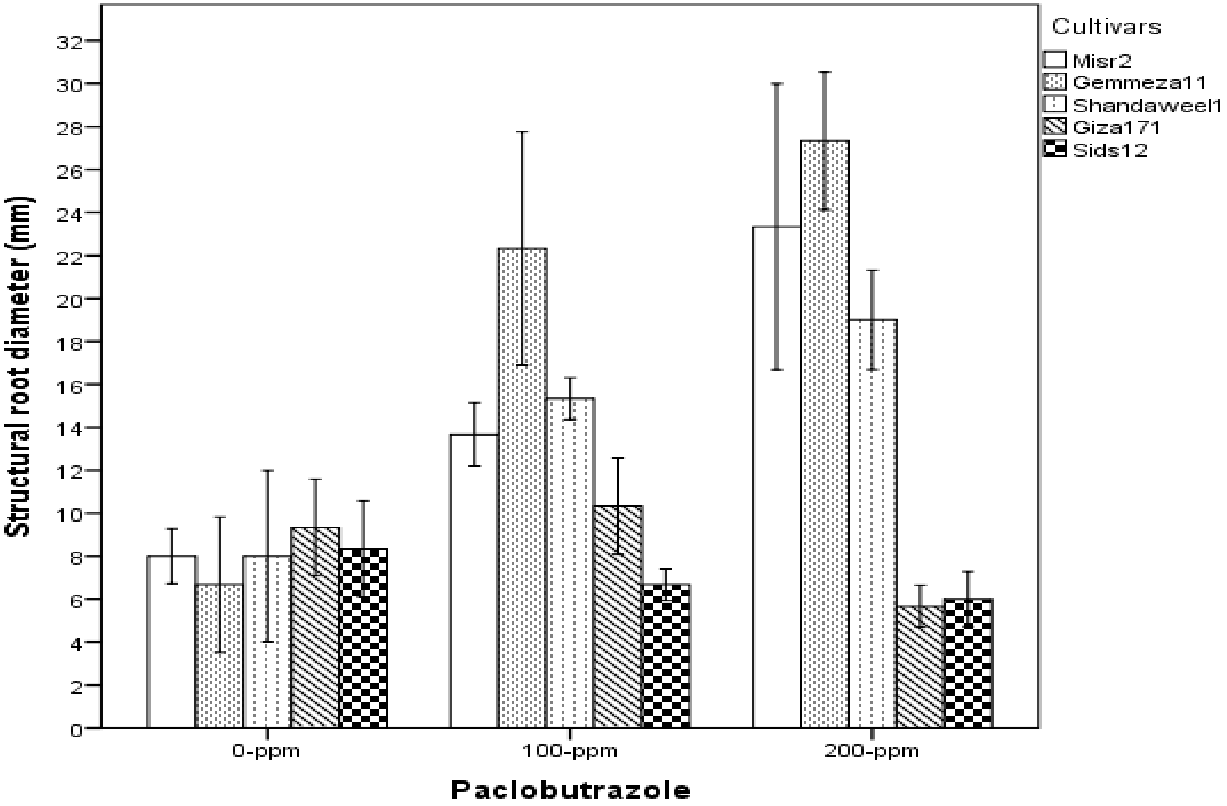
3- Structural root length:

Table (3) shows that structural root length was not changed significantly by PGRs × cultivar interactions. These results were coincided with those observed by Rajala *et al*. (2002)

4- Structural root diameter:

Table (3) showed that structural root diameter was significantly (P<0.01) affected by PGRs × cultivar interactions; and the main effect of cultivar, while did not change significantly by the main effect of PGRs. These results indicate that the strong effect of cultivar rather than PGR treatments on the root diameter. Root diameter for the resistant cultivar group showed positive response for PGR applications at either 100 or 200 ppm, whereas the susceptible cultivars showed no response for these treatments (Figure 1). For instance, at 100 ppm paclobutrazole, root diameter recorded the highest and lowest values at Gemmeza11 and Sids12, respectively, with increase above 70 % (Figure 1). Maximum root diameter for Gemmeza11, Misr2 and Shandaweel1 could be achieved by 100, 200 and 200 ppm, respectively (Figure 1).

Figure 1. Effect of the interaction between PGR treatments and cultivars on structural root diameter of wheat in combine analyses across 2016 and 2017 seasons.



C) Growth:

1- Plant height:

Table (4) shows that plant height at anthesis was not affected significantly by PGRs × cultivar interactions. Similar results were observed by Crook and Ennos (1995) and were not by (Allam *et al*., 2002; Tripathi *et al*., 2004).

2- Number of tillers per square meter:

Table (4) shows that number of tillers per square meter at anthesis was not differed significantly by PGRs × cultivar interactions. Similar results were observed by Rajala and Peltonen-Sainio (2001) and were not by Allam *et al*. (2002).

3- Shoot dry weight per plant:

Table (4) shows that shoot dry weight per plant at anthesis was not varied significantly by PGRs × cultivar interactions. These results were in agreement with those by Tripathi *et al*. (2004).

D) Yield and yield components:

1- Number of spikes per square meter:

Table (5) shows that number of spikes per meter square was not changed significantly by PGRs × cultivar interactions. (Tripathi *et al*., 2004; Ramburan and Greenfield, 2007; Sinniah *et al*., 2012) found similar results.

2- Number of kernels per spike:

Table (5) shows that number of kernels per spike did not chang significantly by PGRs × cultivar interactions. (Ramburan and Greenfield, 2007; Sinniah *et al*., 2012) observed similar results, but Tripathi *et al*. (2004) did not.

3- Thousand kernel weight:

PGRs × cultivar interactions exhibited non significant impact on thousand kernel weight (Table 5). (Ramburan and Greenfield, 2007; Sinniah *et al*., 2012) found similar results, but Tripathi *et al*. (2004) did not.

4- Grain yield per faddan:

Table (5) shows that grain yield was not differed significantly by PGRs × cultivar interactions. These results were matched with those obtained by (Ramburan and Greenfield, 2007; Brinkman, 2012; Sinniah *et al*., 2012). However, treated wheat plants by PGR had increased grain yield as found by (Knapp *et al*., 1987; Berry *et al*., 2000; Alam *et al*., 2002; Tripathi *et al*., 2004).

5- Straw yield per faddan:

PGRs × cultivar interactions exhibited non significant impact on straw yield (Table 5). These results were in contrast with those found by Tripathi *et al*., 2004; Alam *et al*., 2002).

6- Harvest index:

Table (5) shows that harvest index was not varied significantly by PGRs × cultivar interactions. These results were conflicted with those obtained by Tripathi *et al*., 2004; Alam *et al*., 2002).

The second Experiment

Generally, combined analysis (Tables 9, 10, 11) shows that neither year nor year interactions were significant for all traits of study.

IV- Effect of mineral nitrogen rate:

A) Lodging score:

Combined analysis (Table 9) showed that the effect of N rates was not significant for lodging score. These results were in agreement with those observed by (Griffin, 1998; Berry *et al*., 2000; Tripathi *et al*., 2003; Berry *et al*., 2004; Mooney *et al*., 2006) with little exceptions, but were not by (Knapp *et al*., 1987; Crook and Ennos, 1995; Rajkumara, 2008; Brinkman, 2012) as they found that higher N rates increased lodging susceptibility.

B) Root characters:

Table (9) showed that N rates significantly affected all root characters at anthesis except for structural root length and diameter.

1- Root plate spread:

Root plate spread was affected significantly ($P<0.01$) by N rates (Table 9). The spread of the root plate was increased linearly with increasing N rates from 0 to 100 kg N fad^{-1} and these increases were in the range of 24.4 % (Table 9). On the other side, root width was not affected by N rates as found from (Crook and Ennos, 1995; Griffin, 1998). Likewise, Berry *et al*. (2000) reported that lower nitrogen rates resulted in less tillers per plant that minimized the spread of the root plate. However, in the present study tillers m^{-2} had responsed linearly with N rates (Table 10) thus, more tillers could explain a linear relationship between root width and N rates.

2- Number of roots per plant:

Number of roots per plant was affected significantly ($P<0.01$) by N rates (Table 9). Roots plant^{-1} increased gradually with increasing N rates. Maximum number of roots plant^{-1} was 18.2 root at 100 kg N fad^{-1} and significantly exceeded rates of 0, 25, 50 and 75 kg N fad^{-1} by 22, 16.5, 12.2 and 3.6%, respectively (Table 9). However, an inverse relationship between root number and nitrogen has been observed by (Crook and Ennos, 1995; Easson *et al*., 1995). In contrast with above results, Griffin (1998) found that number of roots per plant was not affected by nitrogen rates.

3- Structural rooting depth:

Table (9) shows that structural rooting depth was significantly affected by N rates. It was increased linearly ($P<0.01$) by increasing N rates. Maximum rooting depth was 40.7 mm at either 75 or 100 kg N fad^{-1} and deeper than those which were recorded at rates of 0, 25 and 50 kg N fad^{-1} by 18.3, 12.3 and 7.4 %, respectively (Table 9). However, Thorup-Kristensen (2009) pointed that deeper rooting was related to much lower amounts of nitrogen. On the other hand, Griffin (1998) and Berry *et al*. (2000) found that mineral nitrogen rates did not affect the structural rooting depth. However, all previous researchers had tested N rates on winter wheat not spring wheat as we done.

4- Structural root length:

Structural root length was not affected significantly by N rates (Table 9). However, it slightly increased with increasing N rates with marginal differences in the range of 7.5 %. Similarly, root length was not differed by N rates as observed by Griffin (1998).

5- Structural root diameter:

Nitrogen rates had no significant impact on structural root diameter (Table 9), but it increased slightly with increasing N rates with marginal difference in the range of 13.8 %. Berry *et al*. (2004) mentioned that thicker roots may be caused by a greater proportion of assimilate to be partitioned to the roots. However, higher N rates induced thinner roots as obtained from Mulder (1954) and Easson *et al*. (1995).

6- Root dry weight per plant:

Results of Table (9) show that root dry weight per plant was affected significantly ($P<0.05$) by N rates. Nitrogen rates of either 50 or 75 kg fad^{-1} had produced maximum root dry weight with average 495 mg plant^{-1}, which was heavier than those at either 25 or 100 kg N fad^{-1} by average 11%, whereas at 0 kg N fad^{-1}, root dry weight was minimized by 34% than the first rates (Table 9). Identical results were obtained from Campbell *et al*. (1977a) as they found that root weight of spring wheat was increased curvilinearly with increasing nitrogen rates.

In this study, increased root dry weight per plant by increasing N rates could be indirectly due to the increase in number of tillers per plant (Tables 9, 10). Boatwright and Ferguson (1967) mentioned that each tiller normally develops its own system of adventitious roots. Thus, increased root dry weight by producing more tillers per plant could be mainly due to producing more roots per plant when applied N rates were increased (Tables 9, 10). In addition, Rawson and Hofstra (1967) reported that roots of wheat are poor competitors to other organs when there is a limited supply of available carbohydrates or nutrition. Therefore, proper N rates could be enhanced an adequate assimilates that partitioning in an equilibrium way between shoot and root parts. Consequently, more assimilates in roots were resulted in wider and deeper roots either (Table9).

Table 9. Effects of mineral nitrogen rates and plant densities for lodging score and root characters of wheat in combine analyses across 2016 and 2017 seasons with related analysis of variance.

Main effect	Lodging score	Root plate spread	Roots plant^{-1}	Structural root depth	Structural root length	Structural root diameter	Root dry weight
		mm	no.	mm	mm	mm	g plant^{-1}
Nitrogen (kg fad^{-1})							
0	43.00	31.00	14.22	33.22	123.56	13.89	0.325
25	43.50	34.00	15.22	35.67	128.22	14.22	0.443
50	43.67	37.89	16.00	37.67	130.56	14.89	0.499
75	43.67	40.22	17.56	40.67	133.56	16.11	0.490
100	44.00	41.00	18.22	40.67	134.22	16.11	0.437
LSD (0.05)	NS	0.49	0.32	0.16	NS	NS	0.099
Plant density (no. m^{-2})							
250	0.00	49.47	23.40	44.40	159.13	17.00	0.602
350	58.00	33.07	16.27	35.53	127.27	15.20	0.460
450	72.70	27.93	9.07	32.80	103.67	12.93	0.254
LSD (0.05)	12.37	5.94	3.45	5.07	14.60	NS	0.100
				Significance			
Year (Y)	NS	NS	NS	NS	NS	NS	NS
Rep (year)	NS	NS	NS	NS	NS	NS	NS
Nitrogen rate (N)	NS	**	**	**	NS	NS	*
Y × N	NS	NS	NS	NS	NS	NS	NS
Plant density (D)	**	**	**	**	**	NS	**
Y × D	NS	NS	NS	NS	NS	NS	NS
N × D	NS	NS	NS	NS	NS	NS	NS
Y × N × D	NS	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

C) Growth:

Table (10) shows that N rates significantly affected all shoot characters at anthesis.

1- Plant height:

Plant height at anthesis was significantly ($P<0.01$) affected by N rates (Table 10). It increased linearly with increasing N rates. However, the differences in plant height were not exceeding three centimeters among N rates and it seemed that these centimeters were not a significant concern for lodging behavior in this study. On the other side, higher N rates increase lodging by making plant taller as noticed by (Knapp *et al*., 1987; Crook and Ennos, 1995). However, Berry *et al*. (2000) and Tripathi *et al*. (2003) found that N rates affected lodging score while plant height did not.

Regardless of the lodging behavior, many studies have been found linear relationship between plant height and N rates (Fallahi *et al*., 2008; Attia *et al*., 2013; Namvar and Khandan, 2013). However, Benin *et al*. (2012) observed that plant height was not affected by N rates.

The increase in plant height by increasing N rates could be attributing with the increase in vegetative growth, photosynthesis and meristimatic activity that induced by N application. Consequently, increased cell division, elongation and size, which were resulted in taller plants.

2- Number of tillers per square meter:

Number of tillers per square meter at anthesis was significantly ($P<0.01$) affected by N rates (Table 10). Highest number of tillers m^{-2} was averaged 598 tillers m^{-2} at either 75 or 100 kg fad^{-1}, and significantly exceeded those that were recorded at rates of 0, 25 and 50 kg N fad^{-1} by 25, 21 and 13%, respectively (Table 10). N rates Increased tillers number but did not influence lodging values in this study. On contrary, Griffin (1998), Tripathi *et al*. (2003) and Berry *et al*. (2004) reported that higher N rates increased lodging by producing more tillers per plant. Nevertheless, Berry *et al*. (2000) found that lower N rates resulted in less tillers per plant and this was expected to increase lodging by minimizing the size of root plate and vice versa. In contrast with above results, Crook and Ennos (1995) found that neither number of tillers nor lodging susceptibility were affected by N rates. Regardless of the lodging behavior, many studies found positive respone for the number of tillers by N rates (Campbell *et al*., 1977b; El-Gizawy, 2005; Abdel-Ati and Zaki, 2006; Sidi, 2015). These positive responses could be due to enhance the photosynthetic activity and increasing dry matter per plant that invested for producing more tillers per plant.

3- Shoot fresh weight per plant:

Table (10) shows that shoot fresh weight per plant at anthesis significantly ($P<0.01$) differed by N rates. It increased linearly with increasing N rates. Shoot fresh weight weighed average 16.8 g plant^{-1} at either 75 or 100 kg N fad^{-1}, which was heavier than those at rates of 0, 25 and 50 kg N fad^{-1} by 43.8, 25.6 and 9.9 %, respectively (Table 10). In this study, N rates increased shoot fresh weight at anthesis but did not influence lodging scores. These results were inconsistent with those observed by Berry *et al*. (2004) as they indicated that high rates of nitrogen increased lodging by producing heavy plants. In contrast with above results, Crook and Ennos (1995) found that neither shoot fresh weight nor lodging susceptibility were affected by N rates. Regardless of the lodging behavior, our results were matched with the results of Abdel-Ati and Zaki (2006), as the shoot fresh weight had increased linearly with increasing N rates.

4- Shoot dry weight per plant:

Table (10) shows that shoot dry weight per plant at anthesis significantly ($P<0.01$) differed by N rates. It increased linearly with increasing N rates. Shoot dry weight weighed average 11.3 g plant^{-1} at either 75 or 100 kg N fad^{-1}, which was heavier than those at rates of 0, 25 and 50 kg N fad^{-1} by 44.4, 27 and 10.4 %, respectively (Table 10). More assimilates were partitioned to produce more tillers per plant which were resulted in increased shoot dry weight at anthesis (Table 10). N rates increased shoot dry weight at anthesis but did not change lodging scores in the current study. These results were inconsistent with those observed by Tripathi *et al*. (2003) as they indicated that higher N rates increased lodging scores while it did not affect the dry weight of plants at anthesis. Regardless of the lodging behavior, our results are coincided with the results of (Campbell *et al*., 1977a, 1977b; Abdel-Ati and Zaki, 2006), as the shoot dry weight had increased linearly with increasing N rates.

5- Flag leaf area:

Nitrogen rates had significant impact on flag leaf area (Table 10). It increased linearly with increasing N rates. However, the differences in flag leaf area were not exceeding one centimeter square (0.83 cm2) among N rates. These results were in agreement with those observed by (Abou-Elela, 2001; Abdel-Ati and Zaki, 2006; Benin *et al*., 2012; Sidi, 2015) as the area of flag leaf had increased linearly with increasing N rates. Generally, it has been well known that an adequate supply of N is associated with vigorous vegetative growth that includes flag leaf area.

Table 10. Effects of mineral nitrogen rates and plant densities for shoot characters of wheat at anthesis in combine analyses across 2016 and2017 seasons with related analysis of variance.

Main effect	Plant height	Tillers m^{-2}	Shoot fresh weight	Shoot dry weight	Flag leaf area
	cm	no.	——— g $plant^{-1}$	———	cm^2
Nitrogen (kg fad^{-1})					
0	104.11	446.56	9.43	6.24	46.36
25	104.78	473.67	12.48	8.27	46.62
50	104.67	521.00	15.11	10.09	46.91
75	104.78	596.78	16.74	11.23	47.17
100	106.89	599.78	16.80	11.30	47.21
LSD (0.05)	1.69	48.14	0.42	0.27	0.29
Plant density (no. m^{-2})					
250	93.20	558.27	16.48	12.15	49.83
350	95.40	501.60	14.04	9.11	46.85
450	100.73	522.80	11.81	7.01	43.89
LSD (0.05)	5.16	33.57	3.57	1.50	3.97
			Significance		
Year (Y)	NS	NS	NS	NS	NS
Rep (year)	NS	NS	NS	NS	NS
Nitrogen rate (N)	**	**	**	**	**
Y × N	NS	NS	NS	NS	NS
Plant density (D)	*	**	*	**	*
Y × D	NS	NS	NS	NS	NS
N × D	NS	NS	NS	NS	NS
Y × N × D	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

D) Yield and yield components:

Table (11) showed that N rates had a significance impact on all yield and its components except for number of kernels per spike, thousand kernel weight and harvest index.

1- Number of spikes per square meter:

Number of spikes per meter square was significantly ($P<0.01$) affected by nitrogen rates (Table 11). The highest number of spikes m^{-2} was average 538.4 spikes m^{-2} at either 75 or 100 kg N fad^{-1}, and significantly exceeded those which were recorded at rates of 0, 25 and 50 N fad^{-1} by averaged 25.4, 20.9 and 12.9%, respectively (Table 11). In the present trail, N rates increased spikes m^{-2} but did not alter lodging scores. However, Berry *et al*. (2004) indicated that higherN rates increased lodging by producing more spikes per square meter.

In the absence of lodging, a linear relationship between N rates and spikes m^{-2} were found by (Abedi *et al*., 2011; Hamid *et al*., 2012; Mehasen *et al*., 2015; Sidi, 2015). Our results disagreed with Somarin *et al*. (2010) as they found that the highest number of spikes per square meter could be achieve by only 25 kg N fad^{-1}.

2- Number of kernels per spike:

Nitrogen rates had no significant impact on the number of kernels per spike (Table 11). It was average 36.4 kernels $spike^{-1}$. Similarly, Benin *et al*. (2012) showed that number of kernels per spike was not affected by N rates. However, many studies showed linear relationship between N rates and kernels $spike^{-1}$, as those observed by (Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2015; Sidi, 2015).

3- Thousand kernel weight:

Thousand kernel weight was not differed significantly by N rates and it weighed average 38.8 g (Table 11). The unchanged lodging scores by the main effect of N rate were matched with the unchanged in kernel weight in this study. However, results of Griffin (1998) showed that kernel weight was reduced by increasing N rates due to slight increase in lodging score. Regardless of lodging behavior, our results were matched with Benin *et al*. (2012) as they found that thousand kernel weight was not affected significantly by nitrogen rates. On the other side, Svecnjak *et al*. (2007) found that higher N rates had decreased thousand kernel weight. In addition, the heaviest thousand kernel weight could be achieved by only 25 and 43 kg N fad^{-1} as infered from Somarin *et al*. (2010) and Namvar and Khandan (2013), respectively. Our results were inconsistent with those obtained by (Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2015; Sidi, 2015) as they reported a linear relationship between N rates and kernels weight.

4- Grain yield per faddan:

Grain yield was significantly (P<0.01) affected by N rates (Table 11). Maximum grain yield was average 3181 kg fad^{-1} at either 75 or 100 kg N fad^{-1}, and significantly exceeded those which were achieved at rates of 0, 25 and 50 kg N fad^{-1} by 15.3, 12 and 5.4 %, respectively (Table 11). At higher N rates, lodging was kept unchanged which resulted in higher grain yield (Tables 9, 11). Knapp *et al*. (1987) found that both of lodging and grain yield were increased by 85 and 6.1 % at 76 kg N fad^{-1}, respectively, but the timing of lodging was very late thus, the negative impact of lodging on grain yield was absent. On contrary, Griffin (1998) found that grain yield was reduced by increasing N rates due to slight increase in lodging score.

Regardless of lodging, our results were matched with Hawkesford (2014) as they showed that 75 kg N fad^{-1} was considered an official rate for grain yield in Uk, but differed with those by Somarin *et al*. (2010) as they found that highest grain yield could be achieved by only 25 kg N fad^{-1}. Our results were coincided also with those achieved by (Spaner *et al*., 2000; Haile *et al*., 2012; Mehasen *et al*., 2015; Sidi, 2015) as they reported a linear relationship between N rates and grain yield. On the other side, Namvar and Khandan (2013) found sponential relationship between grain yield and N rates, while (Noureldin *et al*., 2013; Seleem and Abd-Eldayem, 2013) found a cuvilinearly relationship between them. In contrast with above results, Benin *et al*. (2012) found that grain yield was not affected significantly by N rates.

Since all shoot characters were responded positively by increasing N rates, higher grain yield were achieved at higher N rates (Table 10). Evans *et al*. (1975) reported that the stored carbohydrates in mature tillers supplies approximately 10 % of the final grain yield. Moreover, high yielding ability is strongly associated with larger leaves that maximized whether photosynthetic activity or dry matter. Since spikes m^{-2} were responded exponentially by increasing N rates, while kernels spike^{-1} and thousand kernel weight did not, therefore more spikes were mainly explained the higher grain yield at these rates.

5- Straw yield per faddan:

Straw yield was significantly ($P<0.01$) differed by nitrogen rates (Table 11). Maximum straw yield was average 3432 kg fad^{-1} at either 75 or 100 kg N fad^{-1}, and significantly exceeded those which were achieved at rates of 0, 25 and 50 kg N fad^{-1} by 15.4, 10.5 and 8.4 %, respectively (Table 11). These results were agreed with those observed by (Seleem and Abd-Eldayem, 2013; Mehasen *et al*., 2015; Sidi, 2015) as they found that straw yield responded positively with increasing N rates. On the other hand, Noureldin *et al*. (2013) found a cuvilinearly relationship between straw yield and N rates. Our results differed with those by Somarin *et al*. (2010) as they found that highest straw yield could be achieved by only 25 or 50 kg N fad^{-1}. Since vegetative structures of plants were responded positively by increasing N rates in this study, higher straw yield were achieved (Tables 10, 11).

6- Harvest index:

Nitrogen rates had no significant impact on harvest index that was averaged 46.3 % (Table 11). These results were disagreed with those observed by (Mehasen *et al*., 2015; Sidi, 2015) as they found that harvest index was responsed linearly with increasing N rates. In addition, Giambalvo *et al*. (2010) and Attia *et al*. (2013) reported reductions in harvest index at higher N rates, while highest harvest index could be achieved by only 25 kg N fad^{-1} as inspected from Somarin *et al*. (2010).

Table 11. Effects of mineral nitrogen rates and plant densities for wheat yield and its components in combine analyses across 2016 and 2017 season with related analysis of variance.

Main effect	Spikes m^{-2}	Kernels $Spike^{-1}$	Thousand kernel wt.	Grain yield	Straw yield	Harvest index
	——— no.	——	g	——— kg fad^{-1}	———	%
Nitrogen (kg fad^{-1})						
0	401.67	39.06	37.84	2693	3117	46.02
25	426.00	37.49	38.45	2800	3296	45.89
50	469.00	37.17	38.73	3009	3376	47.05
75	537.00	34.17	39.21	3173	3602	46.81
100	539.78	34.16	39.60	3189	3767	45.82
LSD (0.05)	43.42	NS	NS	160	198	NS
Plant density (no. m^{-2})						
250	496.80	42.25	42.00	3219	3643	46.72
350	466.60	34.13	37.30	2880	3328	46.36
450	475.67	32.84	37.00	2820	3324	45.89
LSD (0.05)	30.12	3.00	4.06	244	190.1	NS
			Significance			
Year (Y)	NS	NS	NS	NS	NS	NS
Rep (year)	NS	NS	NS	NS	NS	NS
Nitrogen rate (N)	**	NS	NS	**	**	NS
Y × N	NS	NS	NS	NS	NS	NS
Plant density (D)	*	**	*	**	**	NS
Y × D	NS	NS	NS	NS	NS	NS
N × D	NS	NS	NS	NS	NS	NS
Y × N × D	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

V- Effect of plant density:

A) Lodging score:

The effects of plant density on crop structure which related to lodging susceptibility, were much greater and dominant when compared with the main effect of N rate (Tables 9, 10). Table (9) shows that lodging score was affected ($P<0.01$) severely by increasing plant density per unit area and reached the maximum at 450 kernels m^{-2} with significant 20.2 % higher than at 350 kernels m^{-2}, while there was not any lodging had observed at 250 kernels m^{-2}. Unlodged plants were supplemented always by better root characteristics than lodged plants (Table 9).These results were identical with several studies as those by (Stapper and Fischer, 1990; Crook and Ennos, 1993; Easson *et al*., 1993; Webster and Jackson, 1993; Griffin, 1998; Berry *et al*., 2000; Spink *et al*., 2000; Berry *et al*., 2004) as they found a linear relationship between lodging and plant density. In addition, Nakano and Morita (2009) did not observe any lodging at lower densities as 50 and 150 kernels m^{-2}.

B) Root characters:

Plant density had a significant impact on all root characters except for structural root diameter (Table 9). There are an inverse relationship between plant density and these traits.

1- Root plate spread:

Table (9) shows that the spread of the root plate was differed significantly ($P<0.01$) by plant density and the wider root plate was 49.5 mm at density of 250 plant m^{-2} and more than those which were recorded at 350 and 450 kernels m^{-2} by 33 and 43.5 %, respectively. These results were similar to those observed by (Griffin, 1998; Berry *et al*., 2000; Mooney *et al*., 2006; Sparkes *et al*., 2008; Pinera-Chavez *et al*., 2016) as they reported that low plant population reduced root-lodging risk, mainly by increasing the spread of the root plate. In this study, plant density of 250 kernels m^{-2} produced widest root (49.5 mm) and prevented root lodging. These results are very close to Berry *et al*. (2007) as they concluded that ideotype design for lodging-resistance wheat was associated with a root plate spread of 57 mm. Moreover, Berry *et al*. (2000) mentioned that plant density considered a major determinant of this character which has been related mainly with root lodging. Berry *et al*. (2000, 2003, 2007) and Sparkes *et al*. (2008) considered root width as a key factor for root lodging resistance.

Our results show that at plant density of 250 kernels m^{-2} produced maximum root width and number of tillers per unit area (Tables 9, 10). Similalry, Berry *et al*. (2000) explained the variation in root width by the number of tillers, as it widened by more tillers at lower densities. In addition, Sparkes *et al*. (2008) found that the spread of the root plate was almost exclusively influenced by the quantity of photosynthetically active radiation intercepted per plant at the beginning of stem extension which was taken low values when canopy increase.

2- Number of roots per plant:

Table (9) shows that number of roots per plant was differed significantly ($P<0.01$) by plant density and the highest number of roots $plant^{-1}$ was 23.4 at density of 250 kernels m^{-2} and more than those which were counted at 350 and 450 kernels m^{-2} by 30.5 and 61.2 %, respectively. These results were in agreement with those found by (Easson *et al*., 1993; Griffin, 1998; Whaley *et al*., 2000; Mooney *et al*., 2006; Sparkes *et al*., 2008) as they reported that the number of roots per plant was linearly decreased with increasing plant density. In addition, Sparkes *et al*. (2008) found that reduced number of roots per plant at denser canopies was associated with the reduction in both of quantity (PAR) and quality (R : FR) of light.

Unlodged plants at density of 250 kernels m^{-2} was associated with the maximum number of roots per plant (Table 9). Similalry, greater anchorage strength has been attributed to more roots per plant as reported by (Pinthus, 1973; Easson *et al*., 1993; Griffin, 1998; Sparkes *et al*., 2008). However, Neenan and Spencer-Smith (1975) reported that the number of roots was not response for root lodging.

3- Structural rooting depth:

Table (9) shows that structural rooting depth was differed significantly ($P<0.01$) by plant density and the deepest rooting was 44.4 mm at density of 250 kernels m^{-2} and more than those which were recorded at 350 and 450 kernels m^{-2} by 20 and 26.1 %, respectively. These results were matched with those by (Griffin, 1998; Berry *et al*., 2000) as they reported that lower plant densities have deepened rooting than higher densities.

Table (9) shows that unlodged plants at density of 250 kernels m^{-2} was accompanied with the deepest rooting (44.4 mm). These results are identical with those observed by Kirby (1993) as he mentioned that reducing root lodging has caused by the plant's ability to adjust its crown depth to more than 40 mm. In addition, Griffin (1998) indicated that low plant population reduced root-lodging risk, by increasing rooting depth and he suggested that rooting depth considered as a crucial indicator of lodging risk. Moreover, deepest rooting increases anchorage and root lodging resistance as mentioned by Berry *et al*. (2002, 2003).

4- Structural root length:

Plant density had significant ($P<0.01$) impact on structural root length (Table 4). Root length was inversely proportional to the plant densities; it linearly increased from 103 to reach 159 mm with differences in the range of 35 %. Similar results were inferred from Griffin (1998), as the root length at 220 plants m^{-2} was extended twice than those at 435 plants m^{-2}. These results also are in agreement with those found by (Easson *et al*., 1993; Berry *et al*., 2000; Sparkes *et al*., 2008) as they reported that the structural root length was linearly decreased with increasing plant density. The reduction in root length by increasing plant density was related to the reduction in both of quantity (PAR) and quality (R : FR) of light as explained by Sparkes *et al*. (2008).

5- Structural root diameter:

Although plant density had no significant impact on structural root diameter (Table 9) but root diameter was inversely proportional to the plant densities; it linearly increased from 12.9 to reach 17 mm. These marginal incremental in root diameter at lower plant densities has observed also by Sparkes *et al*. (2008). In addition, Berry *et al*. (2004) explained that thicker roots may be caused by the absence of a strong shade avoidance response by the plant, which stimulates a greater proportion of assimilate to be partitioned to the roots.

Greater anchorage strength has been attributed to thicker roots reported by (Easson *et al*., 1993; Sparkes *et al*., 2008). Moreover, Pinthus (1973) mentioned that diameter of roots have a reasonably close correlation with root lodging, while Neenan and Spencer-Smith (1975) reported that root diameter was not the most response for root lodging.

6- Root dry weight per plant:

Table (9) shows that root dry weight per plant ($P<0.01$) was differed significantly by plant density. The heaviest root weight was 0.602 g plant^{-1} at density of 250 kernels m^{-2} and more than those which were weighed at 350 and 450 kernels m^{-2} by 24 and 58 %, respectively. These results were in agreement with those found by (Easson *et al*., 1993; Berry *et al*., 2007) as they reported that root dry weight per plant was linearly decreased with increasing plant density. Root: shoot ratio decreased with shading at higher densities as understood from (Nelson, 1963; Rawson and Hofstra, 1967). In addition, Sparkes *et al*. (2008) found that reduced dry weight of roots at denser canopies was associated with the reduction in both of quantity (PAR) and quality (R : FR) of light.

Unlodged plants at density of 250 kernels m^{-2} was associated with the heaviest dry weight of root per plant (Table 9). Similalry, greater anchorage strength has been attributed to a heaviest root dry weight per stem as reported by Easson *et al*. (1993). Moreover, Pinera-Chavez *et al*. (2016) found a positive relationship between root dry weight and the most lodging-associated trait as the spread of the root plate. In addition, they concluded that spring wheat might require a great investment in additional root biomass to widen its root plate than winter wheat.

C) Growth:

1- Plant height:

Plant height was significantly ($P<0.05$) affected by plant density (Table 10). Plants were tended to be taller at density of 450 kernels m^{-2} than those at 250 and 350 kernels m^{-2}, by 7.5 and 5.3 %, respectively. Tables (9,

10) show that severe lodged plants at densities of either 350 or 450 kernels m^{-2} was accompanied with the tallest plants. However, the differences in plant height were not exceeding 2.2 centimeters between unlodged and lodged plants at densities of 250 and 350 kernels m^{-2}, respectively, accordingly, plant height was not responsible for lodging behavior in this study. These results are in agreement with Griffin (1998) as he concluded that plant height was found to be unimportant indicator of lodging risk acorss different plant populations. On contrary, Berry *et al*. (2000) found that plant height did not differ between lower and higher densities, but they recommended shorter plants for lodging resistant as well as Berry *et al*. (2003). Later in 2007, Berry *et al* concluded that ideotype design for lodging-resistance wheat should associate with plant height of 0.7 m.

Our results are coincided with those by (Geleta *et al*., 2002; Baloch *et al*., 2010; UIlah, 2014) as they found an increase in plant height with increasing plant density. On the other side, results of us are inconsistent with those observed by Easson *et al*. (1993) as they found a significant reduction in plant height by increasing plant density, while (Hussain *et al*., 2001; Nakano and Morita, 2009) found no differences in plant hight among plant densities.

2- Number of tillers per square meter:

Table (10) shows that number of tillers per square meter at anthesis was affected significantly ($P<0.01$) by plant density. Maximum tillering was 558 at density of 250 kernels m^{-2} and more than those which were obtained at either 350 or 450 kernels m^{-2} by averaged 8.3 %. These results were coincided with those by (Griffin, 1998; Berry *et al*., 2000; Whaley *et al*., 2000) and are not with (Easson *et al*., 1993; Baloch *et al*., 2010) as they found more tillers m^{-2} at higher plant densities. Moreover, Chen *et al*. (2008) found greater mortalities of tillers at higher plant densities such as 323 or 430 kernels m^{-2}.

Unlodged plants at density of 250 kernels m^{-2} was associated with the maximum number of tillers per whether square meter or plant, more roots and widened root plate (Tables 9, 10). Similalry, greater anchorage strength has been attributed to more tillers per plant at lower densities as reported by Griffin (1998). Whaley *et al*. (2000) found that lower populated plants have many tillers which accompanied with more crown roots. Likewise, Berry *et al*. (2000) found a positive correlation between number of tillers per plant and the spread of the root plate which resulted in greater root lodging resistant. In addition, they reported that root lodging was less at lower plant population and this could be related to the late forming tillers which were have small spikes at these densities. However, they mentioned that extreme tillers per plant at lower densities could partially counteract with the root plate effect. Later in 2004 and 2007, they recommended 500 tillers m^{-2} (2.5 tillers plant^{-1}) for ideotype design of lodging-resistance wheat. Our results are almost identical with their findings as the number of tillers per plant for unlodged plants at 250 kernels m^{-2} was 2.2 tiller. However, number of tillers per plant for lodged plants at densities of either 350 or 450 kernels m^{-2} was 1.4 and 1.2 tiller plant^{-1}, respectively. Therefore, 2.2 tillers plant^{-1} at density of 250 kernels m^{-2} was appropriate for lodging resistance in this study, whilst less than 1.5 tiller plant^{-1} at higher densities have tended plants to more susceptible for root lodging. In a like manner, results of Easson *et al*. (1993) showed that less tillers per plant did not improve lodging resistance.

3- Shoot fresh weight per plant:

Shoot fresh weight per plant at anthesis was affected significantly ($P<0.05$) by plant density (Table 10). It was decreased linearly from 16.5 g plant $^{-1}$ at density of 250 kernels m^{-2} to reach 14 and 11.8 g plant^{-1} at densities of 350 and 450 kernels m^{-2}, with total reduction of 14.8 and 28.3 %, respectively. Lodged plants at densities of whether 350 or 450 kernels m^{-2} was associated with lighter fresh weight of plants at anthesis than unlodged plants. These results were identical with findings by Easson *et al*. (1993) as they found that shoot fresh weight decreased by 29.3 % at higher than lower densities and the weaker anchorage strength has been attributed to less fresh weight per plant.

4- Shoot dry weight per plant:

Shoot dry weight per plant at anthesis was affected significantly ($P<0.01$) by plant density. It was decreased linearly from 12.2 g plant $^{-1}$ at density of 250 kernels m^{-2} to reach 9.1 and 7 g plant^{-1} at densities of 350 and 450 kernels m^{-2}, with total reduction of 25 and 42.3 %, respectively. Lodged plants at densities of whether 350 or 450 kernels m^{-2} was associated with lighter dry weight of plants at anthesis than unlodged plants. These results were matched with those by Easson *et al*. (1993), and were not by Stapper and Fischer (1990) as they observed that dry weight of plant at density of 200 plants m^{-2} (less lodged) was lower by 4.8 % than those at 400 plants m^{-2} (high-lodged). Heavier plants at lower densities were inspected also from those by (Wajid *et al*., 2004; Olsen *et al*., 2005; Arduini *et al*., 2006; Nakano and Morita, 2009).

5- Flag leaf area:

Flag leaf area was affected significantly ($P<0.05$) by plant density (Table 10). Flag leaf area was inversely proportional to plant density; it linearly increased significantly from 43.9 to reach 49.8 cm^2 with differences in the range of 12 %. Increased flag leaf area at lower plant density could be due to sufficient assimilates that partitioned well for either increasing tillers per plant or increasing shoot dry weight or increasing the area of flag leaf, while limited assimilate and aggressive competition among plants may restricted the area of flag leaf at higher plant densities.

D) Yield and yield components:

1- Number of spikes per square meter:

Table (11) shows that number of spikes per square meter was differed significantly ($P<0.05$) by plant density and maximum spikes m^{-2} was 497 at density of 250 which did not differ significantly when compared with 450 kernels m^{-2}, but more than those which was recorded at 350 kernels m^{-2} by averaged 6 %. These results are similar with those observed by Lloveras *et al.* (2004) as their results showed similar number of spikes m^{-2} at densities of either 250 or 400 kernels m^{-2}. On contrary, UIIah (2014) found that plant density of 360 kernels m^{-2} produced highest spikes m^{-2} than at 240 or 420 kernels m^{-2}. More spikes per square meter was observed at higher densities as reported by (Easson *et al.*, 1993; Spaner *et al.*, 2000; Hussain *et al.*, 2001; Schillinger, 2005; Arduini *et al*., 2006; Chen *et al*., 2008; Nakano and Morita, 2009; Somarin *et al*., 2010). In addition, denser canopies enhancing the fertility of tillers rather than tillers generative capacity as understood from UIIah (2014).

2- Number of kernels per spike:

Plant density had a significant (P<0.01) impact on number of kernels per spike (Table 11). Kernels spike^{-1} was inversely proportional to the plant densities; it linearly increased from 32.8 to reach 42.3 kernel spike^{-1} with differences in the range of 22.4 %. Results of Stapper and Fischer, (1990) were differed with those by us, as they found that number of kernels per unit area at density of 200 plants m^{-2} (less lodged) was similar to those at 400 plants m^{-2} (high-lodged). Our results are in confirmation with those observed by (Easson *et al*., 1993; Whaley *et al*., 2000; Hussain *et al*., 2001; Schillinger, 2005; Arduini *et al*., 2006; Chen *et al*., 2008; Nakano and Morita, 2009) and (Spaner *et al*., 2000; UIIah, 2014) with little exceptions, but were not by Lloveras *et al*. (2004) as they found similar number of kernels at different plant densities.

3- Thousand kernel weight:

Plant density had a significant (P<0.05) impact on thousand kernel weight (Table 11). Thousand kernel weight was inversely proportional to the plant densities; it linearly increased from 37 to reach 42 g with differences in the range of 12 %. These results are inconsistent with those by Stapper and Fischer, (1990) as they found that thousand kernel weight at density of 200 plants m^{-2} (less lodged) was similar to those at 400 plants m^{-2} (high-lodged). Our results are in confirmation with those observed by (Easson *et al*., 1993; Geleta *et al*., 2002; Lemerle *et al*., 2004; Somarin *et al*., 2010; UIIah, 2014), but were not by (Spaner *et al*., 2000; Hussain *et al*., 2001; Lloveras *et al*., 2004; Schillinger, 2005; Arduini *et al*., 2006; Chen *et al*., 2008; Nakano and Morita, 2009; Baloch *et al*., 2010;) as they found similar thousand kernel weight at different plant densities.

4- Grain yield per faddan:

Table (11) shows that grain yield was affected significantly ($P<0.01$) by plant density and maximum grain yield was 3219 at density of 250 kernels m^{-2} and more than those achieved at either 350 or 450 kernels m^{-2} by averaged 11.5 %. Unlodged plants at density of 250 kernels m^{-2} were associated with maximum grain yield and vice versa for the lodged densities (Tables 9, 11). These results are consistent with those by Easson *et al*. (1993) as they found that grain yield dropped by 25.6 % at higher densities, which were accompanied with higher lodging scores. On contrary, Stapper and Fischer, (1990) found that grain yield at density of 200 plants m^{-2} (less lodged) was similar to those at 400 plants m^{-2} (high-lodged). On the other hand, inconsistent results were observed by Geleta *et al*. (2002) and Wajid *et al*. (2004) concerning the realtionship between grain yield and plant densities.

In this study, all root and shoot growth characters were at higher levels at density of 250 kernels m^{-2} than whether 350 or 450 kernels m^{-2} except for plant height, while root diameter did not change among these densities (Tables 9, 10). In addition, number of spikes was very close among these densities, but the major differnces were observed for kernels number per spike and thousand kernel weight (Table 11). Lodged plants at either density of 350 or 450 kernels m^{-2} have less kernels with lighter weights than unlodged plants at density of 250 kernels m^{-2} (Table 11). Previous studied showed the negative impact of lodging after anthesis on kernels number and its weight as we indicated before. Berry *et al*. (2004) stated that the grain yield reductions could be as much as 50 % and were caused by decreases in the number of kernels per spike and kernel weight. Consequently, less yield at both higher densities than at the lower density in this study, could be explained by the negative effects of lodging rather than the main effect of plant density alone.

Many researchers have found that, in the absence of lodging, yields of spring wheat have increased by increasing plant densities (Spaner *et al*., 2000; Weiner *et al*., 2001; Hussain *et al*., 2001; Olsen *et al*., 2005, 2006; Arduini *et al*., 2006; Khan and Marwat, 2006; Gao *et al*., 2009; Somarin *et al*., 2010; Abd-El-Nasser and Balah, 2011; UIIah, 2014) and the others found similar yields (Lloveras *et al*., 2004; Schillinger, 2005; Chen *et al*., 2008; Nakano and Morita, 2009; Baloch *et al*., 2010). However, only three studies by (Carr *et al*., 2003; Wood *et al*., 2003; Lemerle *et al*., 2004) showed increased in grain yield at lower densities. Consequently, It can be assumed again that the grain yield differences in this study are almost entirely due to the effects of lodging rather than to plant density alone.

5- Straw yield per faddan:

Table (11) shows that straw yield was differed significantly ($P<0.01$) by plant density. Maximum straw yield was 3643 at density of 250 and significantly more than those which were achieved at either 350 or 450 kernels m^{-2} by averaged 8.7 % (Table 11). Unlodged plants at density of 250 kernels m^{-2} were associated with maximum straw yield and vice versa for the lodged densities (Tables 9, 11). These results are consistent with those by Easson *et al*. (1993) as they found that straw yield dropped by 16.5 % at higher densities, which were accompanied with higher lodging scores. Similarly, Schillinger (2005) found that straw yield was declined insignificantly with increasing plant densities. On contrary, Stapper and Fischer, (1990) found that straw yield at density of 200 plants m^{-2} (less lodged) was similar to those at 400 plants m^{-2} (high-lodged). In this study, higher densities produced less vegetative structures than lower density (Table 10). In addition, some rots observed at these higher densities, mainly due to lodging, but was not observed for all lower density plots. These two reasons reasonably explain the reductions in straw yield at higher densities.

In contrast with our results, straw yield had increased by increasing plant densities as found by (Spaner *et al*., 2000; Gao *et al*., 2009; Somarin *et al*., 2010; Abd-El-Nasser and Balah, 2011; UIlah, 2014), or was not differ among plant densities as observed by Chen *et al*. (2008). However, it is important to mention that these findings by them were in the absence of lodging.

6- Harvest index:

Table (11) shows that harvest index was not differed significantly by plant density with average 46.3 %. These results are coincided with those by (Spaner *et al*., 2000; Schillinger, 2005; Chen *et al*., 2008; Gao *et al*., 2009). However, reduced straw yield by increasing plant density was observed by (Stapper and Fischer, 1990; Easson *et al*., 1993; UIlah, 2014), while it increased as inferred from Somarin *et al*. (2010).

VI- Effect of nitrogen and plant density interactions:

Generally, plant densities × N rate interactions were not significant for all traits of this study.

A) Lodging score:

Table (9) shows that lodging score was not affected significantly by plant densities × N rate interactions. These results are matched with Nakano and Morita (2009), while maximum lodging for winter wheat was observed at higher plant densities and N rates, as inspected from Griffin (1998).

B) Root characters:

1- Root plate spread:

Table (9) shows that the spread of the root plate was not differed significantly by plant densities × N rate interactions. On contrary, Berry *et al*. (2000) found that the spread of the root plate was not increased by reducing plant population (250 kernel m^{-2}) when nitrogen rate was at higher level (more than 100 kg N fad^{-1}).

2- Structural root length:

Table (9) shows that structural root length was not changed significantly by plant densities × N rate interactions. Griffin (1998) found that root length was doubled for winter wheat at plant density of 220 with 0 kg N fad^{-1} than at density of 435 plants m^{-2} with 85 kg N fad^{-1}.

C) Growth:

1- Plant height:

Table (10) shows that plant height at anthesis was not affected significantly by plant densities × N rate interactions. These results are coincided with those by Nakano and Morita (2009).

2- Shoot dry weight per plant:

Table (10) shows that shoot dry weight per plant at anthesis was not varied significantly by plant densities × N rate interactions. These results are coincided with those by Nakano and Morita (2009).

D) Yield and yield components:

1- Number of spikes per square meter:

Table (11) shows that number of spikes per meter square was not changed significantly by plant densities × N rate interactions. These results agreed with those by (Spaner *et al*., 2000; Nakano and Morita, 2009), and were not by Somarin *et al*. (2010).

2- Number of kernels per spike:

Table (11) shows that number of kernels per spike did not chang significantly by plant densities × N rate interactions. These results matched with those by (Spaner *et al*., 2000; Nakano and Morita, 2009).

3- Thousand kernel weight:

Plant densities × N rate interactions exhibited non significance impact on thousand kernel weight (Table 11). These results coincided with those by (Spaner *et al*., 2000; Nakano and Morita, 2009), and were not by Somarin *et al*. (2010).

4- Grain yield per faddan:

Table (11) shows that grain yield was not differed significantly by plant densities × N rate interactions. These results are matched with those by (Spaner *et al*., 2000; Anderson *et al*., 2004; Gao *et al*., 2009; Nakano and Morita, 2009), while maximum grain yield was achieved at all possible treatment combinations except for higher plant density with more nitrogen treatment, as inspected from Griffin (1998). Significant interactions between plant densities and nitrogen rate were found by (Somarin *et al*., 2010; Abd-El-Nasser and Balah, 2011).

5- Straw yield per faddan:

Plant densities × N rate interactions exhibited non significant impact on straw yield (Table 11). These results agreed with those by (Spaner *et al*., 2000; Gao *et al*., 2009), and were not by Abd-El-Nasser and Balah (2011).

6- Harvest index:

Table (11) shows that harvest index was not varied significantly by plant densities × N rate interactions. These results matched with those by Spaner *et al*. (2000), and were not by (Somarin *et al*., 2010; Abd-El-Nasser and Balah, 2011).

SUMMARY AND CONCLUSIONS

Experiment I:

Some of the current cultivated cultivars of wheat behaved extreme root lodging during anthesis under the current agronomic practices. Each of Giza171 and Sids12 scored maximum lodging by 64 and 70, respectively, while Misr2, Gemmeza11 and Shandaweel1did not lodge at all. Unlodged cultivars were associated with higher means values for all root and shoot characters at anthesis than lodged cultivars. All root characters such as root plate spread (root width), roots plant^{-1}, , structural root depth, structural root length, structural root diameter and root dry weight plant^{-1} were negatively correlated with lodging score ($P<0.01$). The respective r-values for these traits were -0.54, -0.65, -0.63, -0.75, -0.48 and -0.73. Simple and multiple linear regression analysis had used to predict the most characters responsible for lodging resistant.

Ten traits at lodging time explained individually from 10 % ($P<0.05$) to 56 % ($P<0.01$) of the total variation in lodging score. Nearby 50% of the total variation in lodging score was explained by either root length or root dry weight plant^{-1} or tillers m^{-2} ($P<0.01$). Since lodging is a complicated phenomenon that is influenced by interaction between genotype with environmental factors (wind, rain, surface irrigation, soil), these three traits had explained the total variation in lodging quite well. However, R^2 values for other traits such as plant height, shoot fresh weight plant^{-1} and shoot dry weight plant^{-1} were significantly less than 0.26; roots plant^{-1}, root depth, width and diameter were 0.42, 0.40, 0.29 and 0.23, respectively at $P<0.01$.

Root length was a key variable for explain the variation in lodging behavior it explained the maximum variation in lodging score (R^2= 0.56,

$P<0.01$), and it had represented a constant in best four (two-parameters) combinations in multiple regression analysis, where the R^2 values ($P<0.01$) of root length with either roots plant^{-1} or structural rooting depth or tillers m^{-2} or root dry weight plant^{-1}, were 60, 64, 65 and 66%, respectively. The improvements for R^2 values when root depth was added to the root length in the model, was greater than adding either root width or root dry weight or tillers m^{-2}. These results strongly indicate the unique role of root length and rooting depth together for explain the variation in lodging score. Most of previous studies have suggested, mainly widen roots or more roots plant^{-1} rather than root depth to maximize root lodging resistance. In this study, at denser densities (450 kernels m^{-2}), unlodged plants had more roots that extended vertically and horizontally to increase anchorage root-soil system, but it seemed that the extension of roots vertically was much more responsible for lodging resist rather than other root characters.

Many researchers reported that shorter plants, lighter plants and fewer tillers with widen roots were essential for root lodging. However, in this study, these traits were not responsible for root lodging resistance. More tillers by unlodged cultivars had increased shoot fresh and dry weight, and it seemed that the canopy protection against wind or lodging was due to the number of tillers per square meter rather than their weight. Another beneficial effect of more tillers per plant was partially due to producing more roots plant^{-1}.

Canopy protection against lodging had related to both of plant aerial and underground parts that are work together in complementary way. This protection process by plants works via producing greatest number of tillers per plant that are distributed and spread well against wind and/or higher values of most of root characters, in particularly, the root length that deepened vertically in the soil.

Lodged cultivars yielded averagely 9.7 % less than the total average of the resistant cultivars. Neither nor spikes m^{-2} nor kernels $spike^{-1}$ nor straw yield nor harvest index had differed among all cultivars, but lodged cultivars produced averagely lighter kernel weights than unlodged cultivars by average 15.6 %. Phenotypic correlations supported these findings and showed that each of thousand kernel weight and grain yield were negatively correlated with lodging scores, $r = - 0.45$ and $– 0.51$, respectively at $P < 0.01$, while the others were at insignificant level. Pollination and fertilization processes in inflorescences may be completed at lodging time, thus the number of kernels per spike may not affect by lodging. However, lodging time was before grain development stages, therefore the translocation of assimilate processes from the source to the sink may be restricted by lodged cultivars and leading to reduce thousand kernel weights than unlodged cultivars. It can therefore be assumed that the grain yield loss for lodged cultivars when compared with unlodged cultivars, could be due to the negative effects of lodging in particular lighter kernels rather than the genotypic differences. Within either lodged or unlodged cultivars there were no significant differences for all yield and yield components traits.

Since each of Giza171 and Sids12 have less tillering generative capacity and limited ability to extension their roots vertically in the soil at denser canopies, thus severe lodging observed for them and caused grain yield loss. Consequently, for reducing lodging especially in areas that have adversely weather conditions we recommended either Misr2 or Gemmeza11 or Shandaweel1 for these areas. Concerning the future wheat breeding programs for root-lodging resistance and higher yielding, we suggested introducing taller and deeper roots for root-soil anchorage strength with more tillers per plant.

Foliar application of Paclobutrazol (PGR) at the beginning of tillering and stem elongation stages at whether 100 or 200 ppm, had successfully widened roots, increased roots plant^{-1}, improved root dry weight, increased shoot fresh and dry weights, increased tillers plant^{-1}, and shortened plants. However, all these favorable modifications in shoot and root characters at anthesis by PGR application were still not sufficient to improve lodging resistant. Since PGR applications induced these positive alternations except for lodging behavior, root length, depth and diameter. Therefore, the unchanged lodging behavior was matched mainly with the unchanged in root length and depth. Consequently, PGRs application induced some alternatives in root characters, which had greatly demonstrated the difference between treated and untreated plants for lodging resist. Therefore, using PGRs in this study leaded us successfully to realize the important role of each of root length and depth for lodging resistance.

PGR applications slightly improved grain yield by insignificant 5.6 %. PGR treatments enhanced both of the tillers generative capacity by plants and the fertility of these tillers, which resulted in more spikes m^{-2}. However, PGR applications reduced kernels spike^{-1}, but did not affect kernels weight. Therefore, the insignificant increase in grain yield by PGR was mainly due to the increase in the number of spikes per square meter. Vegetative structures of plants responded positively by PGR treatments, which resulted in more straw yield, but harvest index was kept unchanged. The only interaction of cultivar × PGR levels was observed only for the structural root diameter. There is no need to use PGR for managing root lodging under the cirumestances of this research.

***Experiment II*:**

Root lodging was observed within anthesis stage and severely affected by increasing plant density per unit area. Lodging reached the maximum at 450 plant m^{-2} with 20.2 % higher than at 350 plant m^{-2}, while there was not any lodging had been observed at density of 250 kernels m^{-2}. Lodged plants at density of whether 350 or 450 kernels m^{-2} were associated with grain and straw yields losses by 11.5 and 8.7 %, respectively than unlodged plants at 250 kernels m^{-2}. Unlodged plants were supplemented always by better root characters than lodged plants. All root and shoot growth characters at anthesis were at higher levels at density of 250 plants m^{-2} than whether 350 or 450 plants m^{-2} except for plant height, while root diameter did not change among these densities.

Number of spikes was very close among these densities, but the major differnces were observed for kernels number per spike and thousand kernel weight. Lodged plants at either density of 350 or 450 plants m^{-2} have less kernels with lighter weights than unlodged plants at density of 250 plant m^{-2}. Although the effects of plant density and lodging were confounded in this study, but less grain yields at both higher densities than at the lower, were found to be explained by the negative effects of lodging such as less kernels with lighter weights, rather than the main effect of plant density alone. Less straw yield at lodged densities was probably due to the negative impacts of lodging (such as rots) and/or poorly vegetative structurs than unlodged density. Similar harvest index was observed for all densities.

The effects of plant density on crop structure which related to lodging susceptibility, were much greater and dominant when compared with the main effect of N rate. The interactions between these two factors were insignificant for all traits of study. Lodging score did not change by five N rates ranged from 0 to 100 kg fad^{-1}. All root and shoot characters at anthesis responded positively by increasing N rates, but these responses were insignificant for root length and diameter. Spikes m^{-2} responsed exponentially by increasing N rates, while kernels spike^{-1}, thousand kernel weight and harvest index were did differ significantly by these rates. Since lodging was kept unchanged even at higher N rates that resulted in well developed vagatative structure, Giza171 yielded higher grain and straw yields at these rates, which were at economic level at 75 kg N fad^{-1}. We recommended seeding rate of 45 kg fad^{-1} (250 kernel m^{-2}) and 75 kg N fad^{-1} to achieve higher yields of Giza171 and prevent root lodging.

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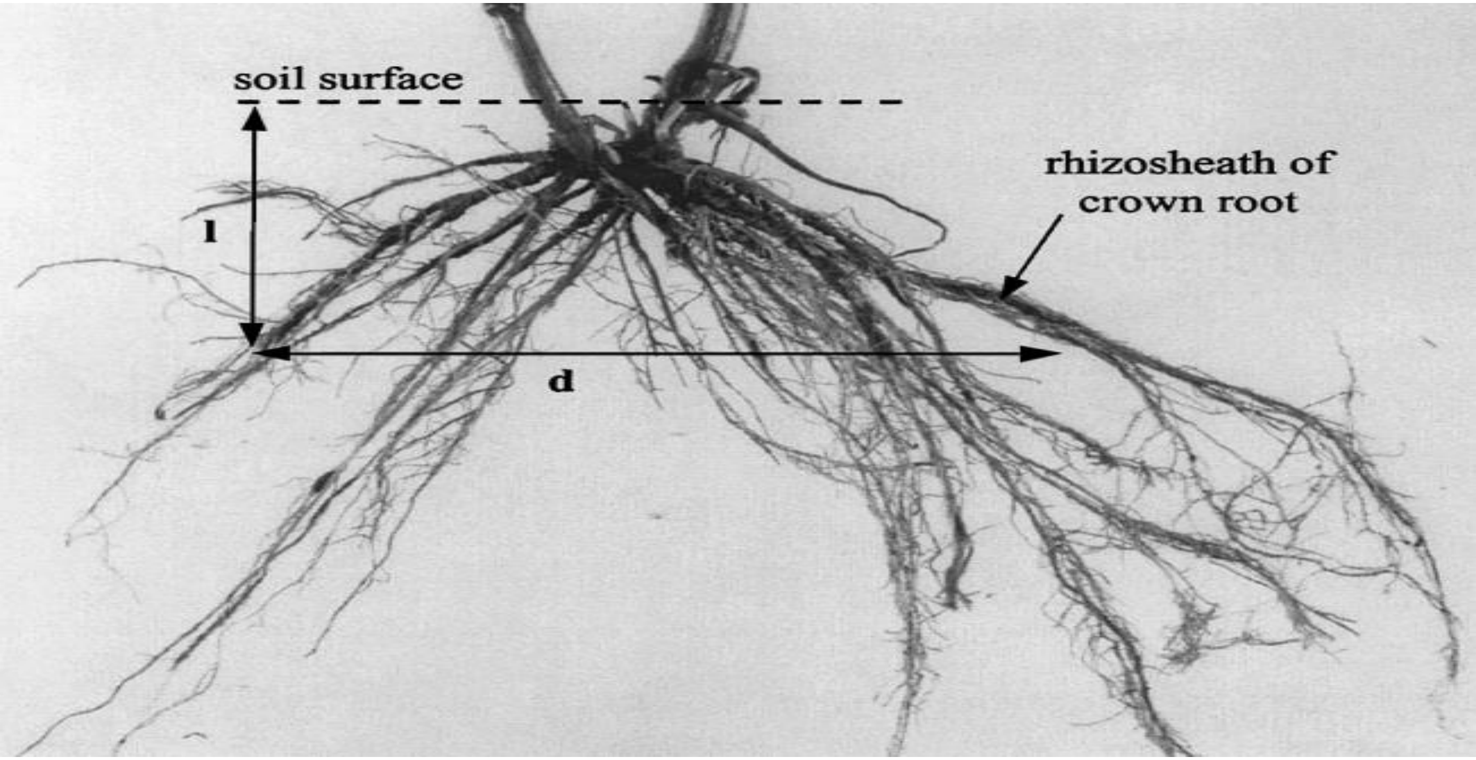
APPENDIX 1

Plate 1. Crown root system of a wheat plant at early milk stage of grains {*d* — root plate spread, *I* — structural rooting depth}, according to Berry *et al*. (2000).



APPENDIX 2

Figure 1. Effect of the interaction between PGR treatments and cultivars on structural root diameter in 2016 season.

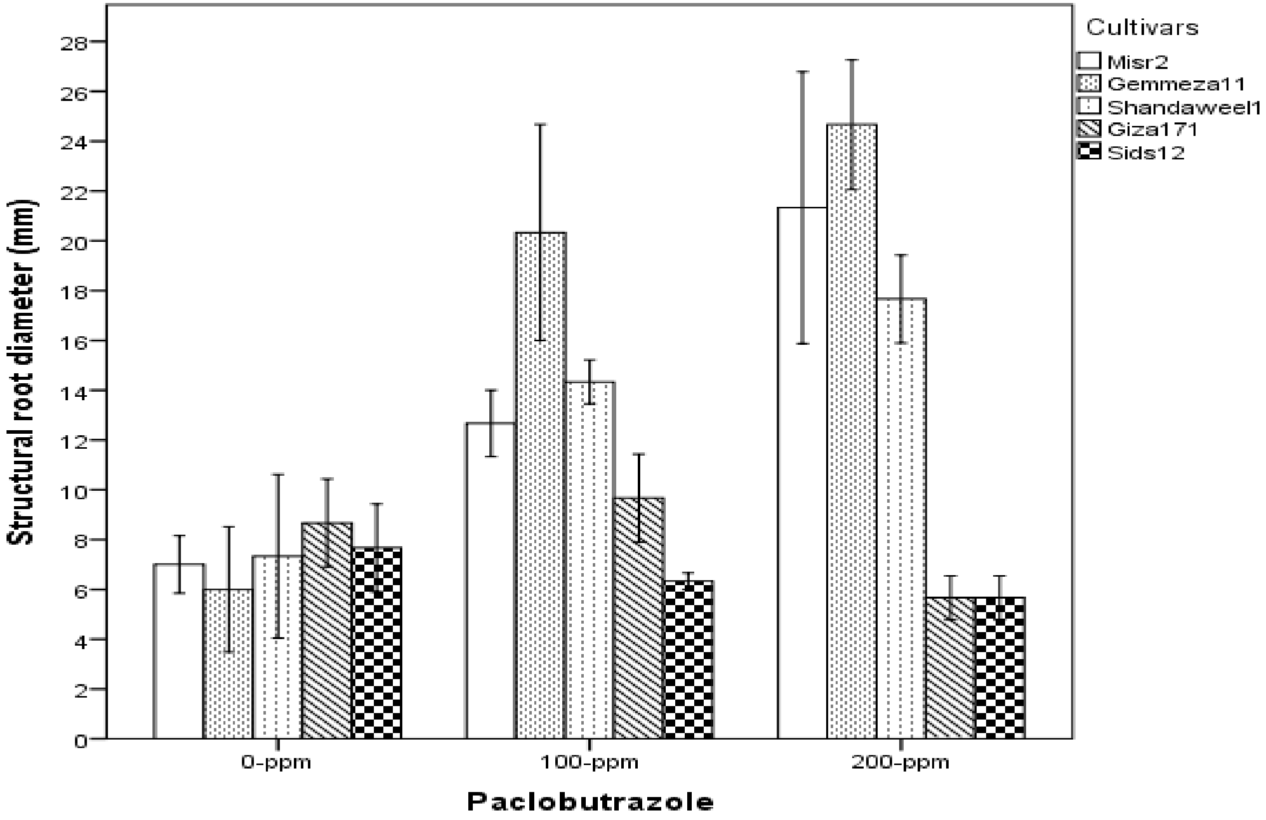
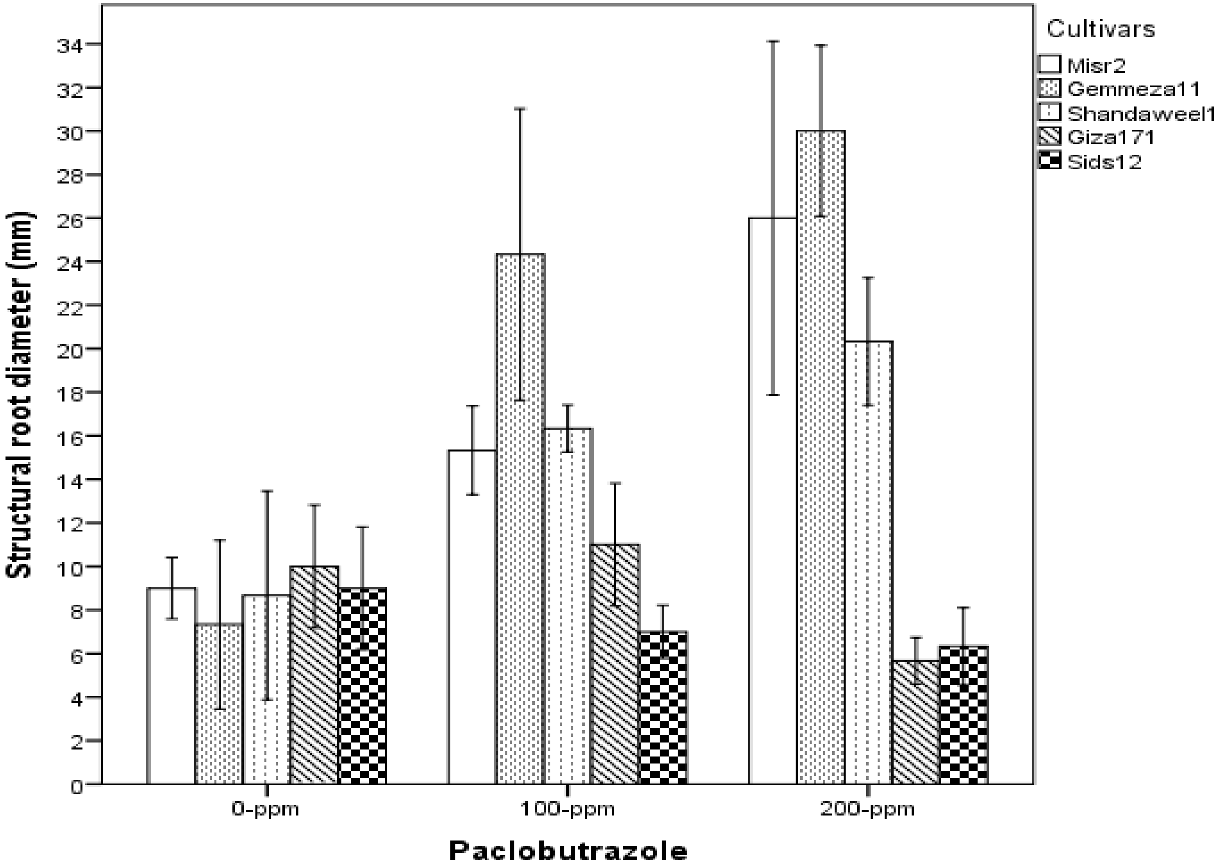


Figure 2. Effect of the interaction between PGR treatments and cultivars on structural root diameter in 2017 season.



APPENDIX 3

Table 1. Effects of PGR treatments and cultivars for lodging score and root characters of wheat in 2016 season.

Main effect	Lodging score	Root plate spread	Roots plant^{-1}	Structural root depth	Structural root length	Structural root diameter	Root dry weight
		mm	no.		mm		g plant^{-1}
Paclobutrazole (ppm)							
0	26.83	19.53	9.13	32.73	111.73	7.33	0.282
100	26.16	29.87	12.80	32.53	113.13	12.67	0.334
200	25.70	32.20	14.13	35.00	114.13	15.00	0.372
LSD (0.05)	NS	6.94	3.67	NS	NS	NS	0.018
Cultivar							
Misr 2	0.00	31.56	13.67	35.89	125.89	13.67	0.377
Gemmeza 11	0.00	35.89	18.22	39.44	147.67	17.00	0.406
Shandaweel l	0.00	28.33	13.44	34.78	116.00	13.11	0.350
Giza 171	62.69	20.22	7.56	29.11	91.00	8.00	0.260
Sids 12	68.47	20.00	7.22	27.89	84.44	6.56	0.253
LSD (0.05)	9.62	8.24	3.32	5.72	13.49	3.69	0.035
				Significance			
Paclobutrazole	NS	*	*	NS	NS	NS	**
Cultivar	**	**	**	**	**	**	**
Paclobutrazole × Cultivar	NS	NS	NS	NS	NS	**	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 2. Effects of PGR treatments and cultivars for lodging score and root characters of wheat in 2017 season.

Main effect	Lodging score	Root plate spread	Roots $plant^{-1}$	Structural root depth	Structural root length	Structural root diameter	Root dry weight
		mm	no.	mm	mm	mm	g $plant^{-1}$
Paclobutrazole (ppm)							
0	28.26	23.07	10.73	38.73	129.60	8.80	0.310
100	27.56	35.53	15.07	38.53	131.00	14.80	0.368
200	27.07	38.27	17.00	41.27	132.13	17.67	0.409
LSD (0.05)	NS	8.87	4.32	NS	NS	NS	0.020
Cultivar							
Misr 2	0.00	38.78	16.67	43.67	147.67	16.78	0.425
Gemmeza 11	0.00	43.22	21.78	47.22	171.44	20.56	0.448
Shandaweel l	0.00	33.44	15.67	40.78	134.44	15.11	0.383
Giza 171	66.03	23.11	8.89	33.56	104.33	8.89	0.281
Sids 12	72.12	22.89	8.33	32.33	96.67	7.44	0.274
LSD (0.05)	10.13	9.69	4.00	6.50	15.55	4.62	0.038
				Significance			
Paclobutrazole	NS	*	*	NS	NS	NS	**
Cultivar	**	**	**	**	**	**	**
Paclobutrazole × Cultivar	NS	NS	NS	NS	NS	**	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 3. Effects of PGR treatments and cultivars for shoot characters of wheat at anthesis in 2016 season.

Main effect	Plant height	Tillers m^{-2}	Shoot fresh weight	Shoot dry weight
	cm	no.	g $plant^{-1}$	
Paclobutrazole (ppm)				
0	112.07	495.00	10.48	6.65
100	95.07	566.73	12.44	7.79
200	85.27	587.80	12.81	8.06
LSD (0.05)	13.29	67.57	0.86	0.79
Cultivar				
Misr 2	100.89	604.11	12.80	8.08
Gemmeza 11	102.67	643.89	13.41	8.37
Shandaweel l	102.22	583.22	11.78	7.39
Giza 171	83.11	465.33	10.94	6.85
Sids 12	98.44	452.67	10.65	6.82
LSD (0.05)	8.53	56.43	0.554	0.653
		Significance		
Paclobutrazole	*	*	**	*
Cultivar	**	**	**	**
Paclobutrazole × Cultivar	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 4. Effects of PGR treatments and cultivars for shoot characters of wheat at anthesis in 2017 season.

Main effect	Plant height	Tillers m^{-2}	Shoot fresh weight	Shoot dry weight
	cm	no.	g $plant^{-1}$	
Paclobutrazole (ppm)				
0	123.00	544.47	11.07	7.02
100	104.47	623.53	13.14	8.23
200	93.93	646.60	13.53	8.51
LSD (0.05)	14.16	74.14	0.90	0.828
Cultivar				
Misr 2	113.78	681.22	13.51	8.52
Gemmeza 11	113.44	711.89	14.15	8.83
Shandaweel l	111.56	637.44	12.44	7.81
Giza 171	90.22	503.78	11.55	7.23
Sids 12	106.67	490.00	11.24	7.20
LSD (0.05)	9.65	61.82	0.58	0.690
		Significance		
Paclobutrazole	*	*	**	*
Cultivar	**	**	**	**
Paclobutrazole × Cultivar	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 5. Effects of PGR treatments and cultivars for wheat yield and its components in 2016 season.

Main effect	Spikes m^{-2}	Kernels $Spike^{-1}$	Thousand kernel wt.	Grain yield	Straw yield	Harvest index
	——— no. ———		g	——— kg fad^{-1} ———		%
Paclobutrazole (ppm)						
0	402.60	33.12	40.53	2640	3040	46.48
100	462.87	29.22	43.24	2779	3278	45.88
200	489.53	28.9	48.88	2816	3407	45.25
LSD (0.05)	66.43	4.22	NS	NS	196	NS
Cultivar						
Misr 2	450.00	27.98	47.73	2915	3392	46.56
Gemmeza 11	462.00	29.80	47.30	2844	3688	43.89
Shandaweel l	457.00	30.77	46.86	2742	3384	46.54
Giza 171	450.78	28.41	39.61	2566	3262	44.74
Sids 12	438.56	28.31	39.58	2551	3165	45.75
LSD (0.05)	NS	NS	6.66	174	NS	NS
			Significance			
Paclobutrazole	*	*	NS	NS	*	NS
Cultivar	NS	NS	*	**	NS	NS
Paclobutrazole × Cultivar	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 6. Effects of PGR treatments and cultivars for wheat yield and its components in 2017 season.

Main effect	Spikes m^{-2}	Kernels $Spike^{-1}$	Thousand kernel wt.	Grain yield	Straw yield	Harvest index
	—— no. ——		g	—— kg fad^{-1} ——		%
Paclobutrazole (ppm)						
0	465.40	30.15	35.03	3054	3568	46.12
100	535.40	26.61	37.38	3215	3848	45.52
200	566.20	26.32	42.23	3258	3999	44.89
LSD (0.05)	77.07	3.81	NS	NS	230	NS
Cultivar						
Misr 2	528.44	24.81	40.66	3423	3982	46.56
Gemmeza 11	536.89	26.97	40.70	3338	4286	43.89
Shandaweel l	529.00	28.12	40.48	3218	3916	46.54
Giza 171	515.89	26.23	34.60	3012	3734	44.73
Sids 12	501.44	26.15	34.62	2995	3619	45.75
LSD (0.05)	NS	NS	5.75	204	NS	NS
			Significance			
Paclobutrazole	*	*	NS	NS	*	NS
Cultivar	NS	NS	*	**	NS	NS
Paclobutrazole × Cultivar	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 7. Effects of mineral nitrogen rates and plant densities for lodging score and root characters of wheat in 2016 season.

	Lodging	Root plate	Roots	Structural root			Root dry
Main effect	score	spread	plant^{-1}	depth	length	diameter	weight
		mm	no.		mm		g plant^{-1}
Nitrogen (kg fad^{-1})							
0	43.78	28.00	13.00	29.67	111.22	12.78	0.299
25	44.00	31.11	14.11	32.22	116.78	13.11	0.409
50	44.56	35.11	14.89	34.33	120.11	13.78	0.463
75	44.22	37.44	16.44	37.33	124.11	14.89	0.458
100	44.67	38.22	17.11	37.33	124.67	14.89	0.408
LSD (0.05)	NS	0.49	0.21	0.47	NS	NS	0.093
Plant density (no. m^{-2})							
250	0.00	45.67	21.73	40.33	146.07	15.73	0.558
350	61.53	30.40	15.20	32.40	116.93	14.00	0.427
450	71.20	25.87	8.40	29.80	95.13	11.93	0.236
LSD (0.05)	13.67	5.55	3.05	4.65	13.40	NS	0.092
				Significance			
Nitrogen rate	NS	**	**	**	NS	NS	*
Plant density	**	**	**	**	**	NS	**
Nitrogen rate × Plant density	NS	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 8. Effects of mineral nitrogen rates and plant densities for lodging score and root characters of wheat in 2017 season.

	Lodging	Root plate	Roots	Structural root			Root dry
Main effect	score	spread	plant^{-1}	depth	length	diameter	weight
		mm	no.		mm		g plant^{-1}
Nitrogen (kg fad^{-1})							
0	42.22	34.00	15.44	36.78	136.00	15.00	0.351
25	43.00	36.89	16.33	39.11	139.67	15.44	0.476
50	42.78	40.67	17.11	41.00	141.00	16.00	0.536
75	43.11	43.00	18.67	44.00	143.00	17.33	0.522
100	43.33	43.78	19.33	44.00	143.78	17.33	0.466
LSD (0.05)	NS	0.57	0.47	0.20	NS	NS	0.106
Plant density (no. m^{-2})							
250	0.00	53.27	25.07	48.47	172.27	18.33	0.645
350	54.47	35.73	17.33	38.67	137.60	16.40	0.493
450	74.20	30.00	9.73	35.80	112.20	13.93	0.272
LSD (0.05)	11.22	6.34	3.85	5.51	15.85	NS	0.107
				Significance			
Nitrogen rate	NS	**	**	**	NS	NS	*
Plant density	**	**	**	**	**	NS	**
Nitrogen rate × Plant density	NS	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 9. Effects of mineral nitrogen rates and plant densities for shoot characters of wheat at anthesis in 2016 season.

Main effect	Plant height	Tillers m^{-2}	Shoot fresh weight	Shoot dry weight	Flag leaf area
	cm	no.	——— g $plant^{-1}$ ———		cm^2
Nitrogen (kg fad^{-1})					
0	100.00	439.11	9.21	6.09	42.56
25	97.56	465.44	12.18	8.07	43.11
50	97.11	510.56	14.75	9.85	43.67
75	97.44	585.89	16.34	10.96	43.89
100	99.44	589.00	16.40	11.03	44.00
LSD (0.05)	1.62	48	0.41	0.27	0.41
Plant density (no. m^{-2})					
250	85.67	547.07	16.09	11.86	46.20
350	87.67	491.53	13.71	8.89	43.47
450	92.53	515.40	11.53	6.84	40.67
LSD (0.05)	4.70	32.77	3.49	1.46	3.63
			Significance		
Nitrogen rate	**	**	**	**	**
Plant density	*	**	*	**	*
Nitrogen rate × Plant density	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 10. Effects of mineral nitrogen rates and plant densities for shoot characters of wheat at anthesis in 2017 season.

Main effect	Plant height	Tillers m^{-2}	Shoot fresh weight	Shoot dry weight	Flag leaf area
	cm	no.	—— g $plant^{-1}$	——	cm^2
Nitrogen (kg fad^{-1})					
0	108.22	454.00	9.66	6.38	50.22
25	112.01	481.89	12.78	8.47	50.11
50	112.22	531.44	15.48	10.33	50.33
75	112.11	607.67	17.15	11.50	50.44
100	114.33	610.56	17.21	11.57	50.44
LSD (0.05)	1.79	48.19	0.43	0.28	NS
Plant density (no. m^{-2})					
250	100.80	569.47	16.88	12.44	53.53
350	103.13	511.67	14.38	9.33	50.33
450	109.00	530.20	12.10	7.18	47.07
LSD (0.05)	5.68	34.40	3.66	1.54	4.19
			Significance		
Nitrogen rate	**	**	**	**	NS
Plant density	*	**	*	**	*
Nitrogen rate × Plant density	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 11. Effects of mineral nitrogen rates and plant densities for wheat yield and its components in 2016 season.

Main effect	Spikes m^{-2}	Kernels $Spike^{-1}$	Thousand kernel wt.	Grain yield	Straw yield	Harvest index
	——— no. ——		g	——— kg fad^{-1}	———	%
Nitrogen (kg fad^{-1})						
0	392.03	39.99	40.67	2477	2961	45.23
25	415.78	38.39	41.44	2590	3148	45.10
50	457.74	38.06	41.56	2789	3247	46.13
75	524.11	34.99	41.89	2958	3496	45.81
100	526.82	34.98	42.33	2976	3658	44.84
LSD (0.05)	42.34	NS	NS	143	157	NS
Plant density (no. m^{-2})						
250	484.88	43.27	45.00	2987	3505	45.82
350	455.40	34.95	40.13	2672	3202	45.46
450	464.25	33.63	39.60	2616	3199	44.99
LSD (0.05)	29.40	3.08	4.36	226	184	NS
			Significance			
Nitrogen rate	**	NS	NS	**	**	NS
Plant density	*	**	*	**	**	NS
Nitrogen rate × Plant density	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.

Table 12. Effects of mineral nitrogen rates and plant densities for wheat yield and its components in 2017 season.

Main effect	Spikes m^{-2}	Kernels $Spike^{-1}$	Thousand kernel wt.	Grain yield	Straw yield	Harvest index
	—— no. ——		g	—— kg fad^{-1} ——		%
Nitrogen (kg fad^{-1})						
0	411.31	38.12	35.11	2908	3272	46.72
25	436.22	36.59	35.44	3010	3445	46.60
50	480.26	36.28	35.78	3228	3504	47.88
75	549.89	33.35	36.56	3387	3708	47.71
100	552.73	33.33	37.00	3403	3877	46.72
LSD (0.05)	44.54	NS	NS	173	239	NS
Plant density (no. m^{-2})						
250	508.72	41.24	39.07	3451	3780	47.52
350	477.80	33.31	34.53	3088	3454	47.16
450	487.08	32.05	34.33	3023	3450	46.69
LSD (0.05)	30.83	2.92	3.69	263	196	NS
			Significance			
Nitrogen rate	**	NS	NS	**	**	NS
Plant density	*	**	*	**	**	NS
Nitrogen rate × Plant density	NS	NS	NS	NS	NS	NS

NS, not significant; *, ** indicates significant at the 0.05, 0.01 levels, respectively.