



## Mechanistic understanding of lodging in spring wheat (*Triticum aestivum*): An Indian perspective

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### ABSTRACT

Lodging in modern spring wheat (*Triticum aestivum* L.) varieties is largely overlooked in India. There is scanty information available in literature for Indian condition regarding the extent, distribution, direct and indirect losses caused by the lodging. Little work has been done on this problem post green revolution period in India. Introduction of dwarfing genes and development of semi-dwarf varieties has resulted in quantum yield gains during 1970-80. After this period till recent years the progress in yield gains are slowed down mainly due to plant architecture of modern varieties not supporting heavier heads inducing lodging. Therefore, the higher potential of genotypes could not be realized to full extent at field level and varieties promising consistent yield level of six tonnes /ha or more are lacking. The complex phenotyping strategies and models designed by the workers working on the problem elsewhere are further impeding the progress as these are not much helpful at field level under Indian conditions. The current paper takes into the consideration the mechanistic approach to understand the problem and correlate the facts and findings of universal nature to design the strategies to manage the lodging through different approaches much suited to Indian conditions.

**Key words:** Lodging, Mechanisms, Plant Types, Productivity, Spring wheat, Varieties

Wheat is one of the most important staple food crops grown over 200 mha in a range of environments throughout the world. The estimated production of world crossed 750 million metric tonnes in 2016-17. India contributed 87 million metric tonnes from 30.22 mha area in 2016-17, a record production of 98.5 million tonnes in 2017-18 from 30.72 mha and forecast of reduction in production in 2018-19 to 94 million metric tonnes (USDA 2018) suggesting a degree of uncertainty in production level.

Despite remarkable growth in wheat production in India, the strong fluctuations in yield levels starting from the onset of green revolution period. In 1965-66 both area and yield were down, 1972-73 yield was down by about 10%; similarly the yield was down during 1979-80, 1986-87, 1989-90, 1997-98, 2004-05 and 2009-10 (Ramdas *et al.* 2014). However, recently the yield of wheat was down to extent that wheat export was zero during 2007-08, 2008-09, 2009-10 and 2010-11 and miniscule level during 2005-06,

2006-07, 2011-12 and 2015-16 and 2016-17 due to erratic environmental conditions in India (Singh *et al.* 2017). Unfortunately, there is no concrete report of losses due to lodging, however, the indirect estimates can be drawn in which lodging played its most important role.

Lodging, the permanent displacement of a cereal stalk from its natural upright position due to internal and external factors is a major limiting factor on food production worldwide (Baker *et al.* 1998, Berry *et al.* 2003, Spink *et al.* 2003). Lodging can be divided into stem lodging and root lodging. Stem lodging results from the bending or buckling of the lower stem internodes (Neenan and Spencer-Smith 1975) (Fig 1). Root lodging results from a failure in root soil integrity so that straight unbroken stalks lean or fall from the crown (Baker *et al.* 1998). The type of lodging that occurs is related to the wheat growing environment (Berry *et al.* 2000, 2003, Spink *et al.* 2003), management regime (Stapper and Fischer 1990, Easson *et al.* 1993), the growth and development period (Berry *et al.* 2000, 2003a, Spink *et al.* 2003) and the varieties grown (Easson *et al.* 1993, Crook and Ennos 1994).

There is inbuilt mechanism of compensation in the crop in response to local stress caused due to environmental factors such as temperature, water and nutrients, however the losses due to lodging are devastating in nature and there is hardly any chance of recovery of yield once it is caused at reproductive stage to grain filling.

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Fig. 1 Stem lodging in wheat entries in IARI New Delhi (Photo by first author).

Most of the literature available on lodging in small grain crops published before 1980 reported the correlations between morphological traits and lodging resistance by observing naturally or artificially induced lodging (Clark and Wilson 1933, Brady 1934, Atkins 1938, Atkins and Ennos 1938, Heyland 1956, Vaidya and Malkani 1963, Pinthus 1967, 1974, Neenan and Spencer-Smith 1975, Stanca and Jenkins 1979). By this time most of the Indian workers were of opinion that semi-dwarfing genes will be strong enough to tolerate lodging.

Two of the landmark varieties Kalyan Sona and HD 2329 were clear winner due to their height being lesser than 90 cm and culm being solid at lower internodes. But after replacement of HD 2329 it was understood that height of the varieties cannot be reduced further in order to keep source-sink balance to raise the yield levels which is evident from the fact no ruling variety after is equal or shorter than HD 2329.

Meanwhile, mechanical models for lodging resistance based on physical formulae and components of the plant and their histological distribution had been reported by workers during 1980-1990s (Jezowski *et al.* 1987, Akira Kokubo *et al.* 1989, Doliński 1990, Doliński and Tarkowski 1990, Ennos 1991, Crook and Ennos 1993, Crook *et al.* 1994) reported high correlations between the cellulose content of barley cell walls and the maximum bending stress. (Gartner *et al.* 1984, Gartner 1984) explained the role of silica deposits in the epidermis of wheat culms in lodging resistant variety. It was the time wherein the importance of lodging was being realized especially in winter wheat having high yield potential and Indian yield levels were growing at slower pace owing to major area under spring wheat and the yield levels beyond 5 tonnes were difficult to realize even under best management conditions.

The major wheat producing countries of Asia especially India where the population pressure is at its boom, any loss of yield is worth counting and saving. Present paper is an effort to describe the mechanistic understanding of lodging and its effect on wheat production with the ameliorative measures. Therefore, the current review takes insight of causes and effects of lodging and the best possible ways suited to Indian conditions for minimizing the losses through all possible approaches including mechanistic (physiology, anatomy,



Fig 2 Root lodging.

chemistry and breeding) and agronomic management of nutrients and water.

#### *Mechanics of lodging*

Lodging is induced by high speed winds and the forces exerted on the plants can lead to structural failure, either the uprooting of whole plants or else the breaking or buckling of stems. This process of plants being laid flat by the wind is called lodging. The commonest form of lodging in wheat is buckling of the stem. In wheat, barley and oats, stem lodging is usually caused by one of the bottom two internodes buckling which results in the upper stem and ear lying horizontally (Mulder 1954, Neenan and Spencer-Smith 1975).

The occurrence of lodging depends on the forces exerted on the plant by wind, rain, etc., on the height from the ground at which they act, and on the strength of the stem (Grace 1977, Niklas 1992).

In case of wheat the force due to the wind acts primarily on the head of the plant which induces a torque or turning moment that increases down the stem and causes bending.

$$\tau = rF \sin \theta \quad (1)$$

wherein  $\tau$  indicates the torque,  $r$  is radius from axis of rotation from point of application of force,  $F$  is the force applied and  $\sin\theta$  is the sine of angle  $\theta$  to which the stem is bending. The torque is resisted by the bending-resistance moment of the stem. The maximum bending-resistance moment is called the stem strength which will be depending upon factors derived from eqn (1).

The height of plant which acts as radius, the surface area of ear head and more particularly the center of ear head which act as point of application of wind force and the threshold angle up to which the plant can bend reversibly and the amount of force applied by wind. It means the bending strength will depend upon the elasticity power of stem as well. The bending point of stem could be determined by the weakest point of stem and will be depending upon the center of mass of stem. Furthermore considering the wheat stem a cylinder the Young Modulus of elasticity can help

us understand the nature of stem being elastic or brittle.

$$YM = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\Delta l/l} = \frac{F \times l}{A \times \Delta l} \quad (2)$$

wherein F denotes the force applied, l is the length of cylinder and  $\Delta l$  is change or distortion in length, A is area and as a matter of fact the metals are more elastic than rubber therefore the solid stem will be giving better elasticity. The area can be managed by the diameter of stem that thicker are the stems larger will be the area and better will be the elasticity.

The applied force will be further aggravated if the airstream contains denser particles such as rain drops and ice particles as these can increase the force exerted on the plants by impacting on it, partly because the denser particles have greater inertia and consequently less tendency to be diverted in the streamlines round the plant (Hamlyn 2013).

For a large enough object, the separate impulses of individual raindrops are equivalent to a steady force given by the mass of water impacting each second  $\times$  velocity. The tendency to lodge will also be enhanced if the frequency of turbulence in the wind corresponds to a natural resonant frequency of the plant, or if the stem is weakened by disease or moisture absorption (Wang *et al.* 2012). Niu *et al.* (2012) discussed the mechanical tools for estimating the power of wind to cause lodging by use of Bernoulli's equation.

According to the Bernoulli equation, standard wind pressure, i.e. the force corresponding to a certain wind speed can be calculated from the following equations

$$W_0 = \frac{r \times v^2}{2g} \quad (3)$$

where  $W_0$  is the standard wind pressure ( $\text{kN/m}^2$ ), r is the air density ( $\text{kN/m}^3$ ), v is the wind speed (m/s), and g is the acceleration due to gravity ( $\text{m/s}^2$ ).

As there are differences in air pressure, temperature, humidity, latitude and other conditions for different places,  $W_0$  calculated needs to be revised according to the corresponding conditions found at the experiment site following equation.

$$\frac{V_z}{V_1} = \frac{\log z - \log z_0}{\log z_1 - \log z_0} \quad (4)$$

where  $V_z$  is the wind speed at height Z (m),  $V_1$  is the wind speed at height  $Z_1$  (m), and  $Z_0$  is the roughness of the ground.  $Z_0$  changes with the environmental conditions. If it is assumed that  $V_z$  is the wind speed measured at a meteorological station ( $Z = 10$  m height);  $V_1$  is the wind speed that directly causes wheat lodging in the field. Baker *et al.*, (1998) reported that the wind at 2 m height above the ground or at 1 m above crop canopy can penetrate the canopy (wheat plant height used in Baker *et al.*'s experiment was 1 m).

The understanding of mechanics of lodging is useful to breeders and agronomists to manage the lodging inherently as well as physical management by designing the lodging resistant genotypes with corresponding package

of practices.

#### *Temporal and spatial variation in lodging*

Temporal variation in lodging occurs due to the time and stage of crop when the lodging is induced while spatial variations occur due to the differential intensity of lodging in different parts of area under crop. Geographical and climatic factors have had a substantial influence on the genetic background of the germplasm and on agronomic management practices. The pattern of lodging can be studied in a particular area owing to the impact of climatic factors during the differential years. For example the lodging was observed in larger area in north western plain zone (NWPZ) of India in most of the irrigated area owing to rainfall and stormy winds during grain filling stage.

The annual reports of All India Coordinated Wheat and Barley Improvement Project (AICWBIP) of years 2014-15, 2015-16, 2016-17 and 2017-18 clearly suggested that large number of test entries (30-50%) in NWPZ suffered lodging of differential intensity in different testing locations. There was incidence of low and high lodging mainly due to difference as low as one week in sowing date across the locations during the window of timely sown area. Though there is no matrix or equation standardized so far estimating the yield and quality losses caused by lodging yet the range of the strong yield fluctuations at different locations indicate the loss attributable to lodging through erratic environmental event.

A very informative article published by Niu *et al.* (2016) discussed the area and degree of lodging in China during 2007 to 2014. The results showed that strong wind's lodging accounted for 8% of the instances studied, continuous rainfall's lodging accounted for 19% and strong winds-heavy rainfall's accounted for 73%. The minimum instantaneous wind speed that could cause large-scale lodging was closely related to rainfall. Without rainfall, the wind speed that resulted in lodging ranging in severity from slight to severe (Level 2 to Level 5) was 14.9 m/s, 19.3 m/s, 21.5 m/s, and 26.5 m/s, respectively; when accompanied by rainfall, the wind speed that resulted in lodging of the same severity decreased linearly with the increase of rainfall. These results will be particularly useful in preventing and alleviating wheat lodging as well screening wheat varieties with good lodging resistance.

There is urgent need for quantifying the yield losses in wheat due to lodging through experimentation under Indian conditions so that a best fit model could be devised taking into considerations of rainfall, wind velocity, stormy events during the crop period especially under irrigated environment and accordingly the smart genotypes could be designed. The due consideration to following factors needs to be given for better understanding and tackling of this problem.

#### *Effects of lodging*

The lodging of cereals decrease the harvestable yield either by effects on photosynthesis, e.g. as a result of either poor light penetration in the compressed canopy or stress

caused by the damaged conducting system or else by making the grain difficult to harvest. Root lodging significantly alters the number of pores irrespective of soil type, whilst lodging has the most significant impact on pore shape under high density wheat in the clay soil, wherein pore shape changes from rounded to irregular however, there is lesser structural disturbance in pore area in the sandy loam soil as compared to the clay and silty loam soils (Tams *et al.* 2004).

Experiments with natural and artificially-induced lodging have measured yield losses caused by lodging which range between 0 and 80% (Mulder 1954, Laude and Pauli 1956, Weibel and Pendleton 1964, Fischer and Stapper 1987, Stapper and Fischer 1990b, Easson and White 1993). Artificial lodging at the ear emergence, milk, soft dough and hard dough stages reduced yield by 31%, 25%, 20% and 12%, respectively (Weibel and Pendleton 1964), Pendleton 1964). Stapper and Fischer (1990) showed that the quantity of yield loss could be related to the number of days lodged during the grain-filling period.

Fischer and Stapper (1987) showed that stems lodged at 45° resulted in less yield loss than stems lodged at 80°. Early lodging mainly reduces the number of kernels/head and later lodging reduces the size of the kernel. Crops which lodge before anthesis often have smaller yield losses than crops that lodge soon after anthesis (Fischer and Stapper 1987).

Protein content of the grain is generally higher in lodged than standing wheat. The total amount of protein per acre, however, will be less in lodged areas (Laude and Pauli 1956). Grain quality can also be degraded due to lodging by affecting grain size and grain specific weight (Lang *et al.* 2012). Lodging causes bending of cereals to ground, which result in the higher susceptibility of grain to fungal attack (Foulkes *et al.* 2011). Hirano *et al.* (1970) also noted lodging-induced reduction in milling quality in bread wheat.

Root lodging can significantly reduce soluble solids and juice brix value which is reported up to 32% (Fedenko *et al.* 2015). The other mechanisms related to lodging-induced effects on yield reduction are reduced mineral translocation and carbon assimilation during grain filling, enhanced respiration and chlorosis, loss of chlorophyll contents due to shade effects, and greater susceptibility to pests and diseases (Foulkes *et al.* 2011). The most likely mechanism appears to be associated with reduced carbon assimilation (Zhu *et al.* 2006).

With delay in lodging, there is decrease in amylose contents and increase in peak viscosity, hot paste viscosity, and final viscosity (Zhong and Cheng 2003) which will impact flour recovery will further affect the bread, biscuit and chapatti quality.

Lodging results in the bending of cereal plants to ground surface; thus, humid conditions around lodged plants increase the susceptibility of fungal attack as evident from the finding by Nakajima *et al.* (2008) that when lodging occurred, deoxynivalenol production was very high irrespective of any fungicide treatment indicating a positive interaction between lodging and mycotoxin levels.

### *The factors influencing the lodging*

*Environmental factors:* Wind speed and rainfall intensity greatly affect the lodging severity at the grain-filling stage. A wind velocity of 9.0 m/s without rainfall can cause slight lodging while the severity increases in multiplicative manner with the increase in speed at ICAR- IARI, New Delhi fields in most of the high-yielding varieties and entries (first author's unpublished data) which is in line of agreement with the work of Liyuan Niu *et al.* (2016). When accompanied by rainfall, the instantaneous minimum wind speed that results in lodging of the same severity decreases linearly with rainfall, with light rain, the required wind speed was 95% (8.55 m/s) which resulted in the same severity of lodging in the absence of rain, the corresponding decrease with moderate rain being 87% (7.83 m/s); with heavy rain, 75% (6.75 m/s); and with torrential rain, 49% (4.41 m/s) (Liyuan Niu *et al.* 2016)

Globally, climate variability accounts for roughly a third (32–39%) of the observed yield variability. In India and China, the top two global wheat producers, average 32 and 31% of yield variability respectively, was explained by climate variability in 71 and 62% of their wheat harvested lands. In China precipitation variability explained most of the variability; in India temperature and precipitation variability were equally important (Ray *et al.* 2015). The food grain production of India has a proportional relationship to the monsoon, with its critical dependence on the onset, duration and distribution of rainfall and the periods of break monsoon conditions (Singhvi and Krishnan). Physical considerations and model studies indicate that tropospheric warming leads to an enhancement of moisture content of the atmosphere and are associated with an increase in heavy rainfall events. In spite of considerable year-to-year variability, there are significant increases in the frequency and the intensity of extreme monsoon rain events in central India over the past 50 years (Goswami *et al.* 2006). This is probably applicable to wheat season wherein the sudden changes in temperature in plains of NWPZ, desert of Rajasthan and snowfall events in lower and Himalayan states leads to tropospheric changes inducing unwarranted rain or storm during 15 January- 15 February when larger area of crop is under heading to grain formation stage.

The effects of elevated CO<sub>2</sub> combined with high temperature and terminal drought on the yield traits studied by Dias de Oliveira *et al.* (2015) hypothesized that wheat genotypes with more sink capacity ( e.g. high tillering capacity and leaf area) have more grain yield under combined elevated CO<sub>2</sub>, high temperature and terminal drought. Keeping these interactions in perspective and events of increased pollution in northern India during winter season farmers are more likely to have concurrence of irrigation and fertilizer application events in response to crop. The windy conditions soon after or during flowering and in early grain filling often can cause significant lodging as the application of water reduces the soil strength and weakening plant anchorage (Ray *et al.* 2015, Piñera-Chavez *et al.* 2016) interpretation is applicable and relevant to NWPZ of India.

Similar events are forced by sudden rise of 2-3°C in temperature especially during night at peak grain filling stage of crop during 20 Feb-March in India tempt farmers to irrigate the fields due to high evapotranspiration. This is coincidence with the temporal changes in local climate of Rajasthan (Desert) and event of snowfall in lower Himalyan range induces high speed winds due to changes in relative atmospheric pressure impacting major area of wheat grown in Haryana, Punjab, western UP, Delhi, and Uttarakhand of NWPZ.

*Physio-chemical factors:* The most obvious mechanisms of lodging in wheat and for that matter in any crop are attributed to physiological processes which are affected due to mechanical forces induced by the lodging factors. Distortion in the physical skeleton of wheat plant due to lodging forces results in failure of vascular system to effectively mobilize the stem reserves to sink and thereby affecting the grain size, grain weight etc. resulting losses in yield. Positive associations have been reported for number of vascular bundles with the lodging resistance (Khanna 1991) probably larger number of bundles work as bypass for the broken routes of xylem and phloem tissues resulting in better recovery and grain filling. Photosynthetically active radiation (PAR) and Red: Far red light ratio (R: FR) have been found to affect the lodging mainly attributed to shading effect of fellow plants on root development reducing the length of structural roots and thereby affecting root plate development and lodging (Sparkes and King 2008). A canopy synthesis model for based on PAR from both direct and diffuse sources has been suggested by Campbell and Norman (1989) which was used for predicting yield losses due to lodging by Berry and Spink (2012).

Therefore solid stem and larger diameter could be used as traits of choice for increasing number of vascular bundles while the handy tools for measuring PAR could be used for estimating the losses due to lodging under Indian conditions as well.

Chemical composition such as cellulose, hemicellulose, carbohydrates, and lignin and silicon contents of stem also

played a significant role in stem strength and rigidity of basal stem and thus affects lodging in cereals (Kong *et al.* 2013). Lignin is a vital structural component of secondary cell wall that not only is related to growth of plant but also provides strength to plants (Ma and Yamaji 2006). The lignin and cellulose contents were higher in the mechanical tissue layer, where the cells around the vascular bundles are rich in lignin and cellulose (Cenci *et al.* 1984). Kokubo *et al.* (1989 a,b) reported high correlations between the cellulose content in barley cell walls and the maximum bending stress. Gartner *et al.* (1984) found that silica deposits in the epidermis of wheat culms were more abundant in a lodging resistant variety than in a variety more sensitive to lodging. In wheat, a significant correlation was observed between stem strength and lignin contents in stem and found that the lower is the lignin accumulation; the higher will be the vulnerability towards lodging (Peng *et al.* 2014). This study further suggested that cultivars with higher lignin accumulation could be a viable alternate for imparting heritable mechanical strength. Furthermore, (Berry *et al.* 2003b) substantiated that lignin and hemicellulose contents together increased the stem strength and thus increase lodging resistance, while significant reduction in the accumulation of these chemicals resulted in higher lodging index. Cellulose also has a qualitative effect on stem strength and increases stem rigidity (Reddy and Yang 2005).

Therefore the assay of chemical composition of wheat stem provide a better phenotyping tool for improving lodging resistance and the method has been used successfully by past workers. However, the energy budgeting among different processes of structural carbohydrate *vis-a-vis* storage carbohydrates, i.e. starch in grain will be matter of investigation unless sufficient source for latter is available. The silica content in wheat and rice straw cannot be increased beyond a level which start impeding the preference of dairy livestock especially under northern India conditions wherein there is already shortage of fodder.

The role of glycine rich proteins (GRP) in lodging resistance have been advocated by several workers. GRPs

Table 1 Some approaches to quantify lodging

Method	Mechanism	Reference	
Visual measurements	Strong wind speed induced	Elasticity, bending strength	Harrington (1950)
Breakdown test	Wheat stalk flexibility		Murphy <i>et al.</i> (1958), Niu <i>et al.</i> (2012)
Wind tunnel	Elasticity, bending strength		Bauer, 1964)(Sterling <i>et al.</i> , 2003)
Stem and root characteristics	Biochemical/ Physical		Crook and Ennos (1994)
Weighted ply board to flatten the plot	Recovery after induced lodging		Briggs (1990), Kelbert <i>et al.</i> (2004), Navabi <i>et al.</i> (2006)
Force to break second internode	Stalk bending strength		Wang and Li (1997), Niu <i>et al.</i> (2012)
Prostate tester	Single stem strength		Xiao <i>et al.</i> (2002), Niu <i>et al.</i> (2012)
Root lodging instrument	Bending momentum strength		Berry <i>et al.</i> (2003)
Electronic device	Physical strength		Niu <i>et al.</i> (2012)
Electrical measurements and root morphological traits	Electrical conductivity		Wu (2016), Wu (2016)

are probably structural proteins which play roles in plant vascular systems and wound healing (Showalter 1993). The predicted beta-pleated sheet secondary structure of cell wall GRPs (Condit and Meagher 1986) may provide elasticity and tensile strength during vascular development resulting in enhanced elasticity of culms (Winzeler *et al.* 1999). It has also been suggested that GRPs either serve as nucleation sites for lignifications (Keller 1993) or form links with other wall proteins and polymers. Now a days the protein assays which are time consuming are replaced by the gene based marker system wherein the target protein expression can be modified by suitable corresponding alleles provided there is enough variability in gene sequence.

#### Phenotyping and measuring lodging extent

The indirect indices based on the average production and productivity of a state or country gives no clear picture of yield reduction owing to specific reason in specific pocket. The complexity of problem is further aggravated by lack of proper knowledge for estimating the lodging in its quantitative and qualitative form at farm level. There are different approaches used by workers to estimate the extent and nature of lodging in order to quantify the losses at experimental level (Table 2).

Despite the literature available on estimation of yield losses due to lodging in experimental fields is available from different corners of world there is limited insight into Indian scenario. The vast area under crop under different cropping systems and across different states and multiple management levels it seems to be a bigger task but it can be done with the available information on tools and techniques with suitable modification according to Indian perspective.

#### Management options to reduce lodging

**Genetic improvement:** During the last century, genetic gain in wheat yield ranged annually from 0.3% to 1.0% (Graybosch and Peterson 2010) which is true for Indian conditions as well (Gupta *et al.* 2017). Genetic gain has largely been attributed to reduced plant height with better allocation of assimilate toward sink resulting in significantly improved harvest index (HI) (Foulkes *et al.* 2010). Further improvement in HI is very hard to come as modern cultivars are very close to theoretical limits of 0.62 (Álvarez *et al.* 2008 a,b; Austin *et al.* 1980). Increased biomass with inbuilt lodging tolerance advocated as a mean of achieving a breakthrough (Sadras and Lawson 2011, Sanchez-Garcia *et al.* 2013). Plant height has been the most discussed character positively correlated with lodging. Introduction and adoption

Table 2 List of Rht genes discovered and utilized in wheat

Gene	Location	Source variety	Reference
Rht-B1 (Rht1, Sd1)	4BS	Norin 10	Allan (1970), Flintham <i>et al.</i> (1997)
Rht-D1 (Rht2, Sd2)	4DS	Norin 10	Allan (1970), McVittie <i>et al.</i> (1978)
Rht3 (Sd3)	4BS	Tom Thumb	Hu (1974), McVittie <i>et al.</i> (1978)
Rht4	Unknown	Hexaploid stock <i>Burt ert1Mutant1</i>	Ellis <i>et al.</i> (2005)
Rht5	Unknown	Hexaploid stock <i>Marfed ert1Mutant1</i>	Konzak <i>et al.</i> (1984), Mcintosh <i>et al.</i> (2003)
Rht6	Unknown	Hexaploid stocks <i>Brever, Burt, Norin 10- Brever14</i>	Konzak <i>et al.</i> (1984), Mcintosh <i>et al.</i> (2003)
Rht7	2A	Hexaploid stocks <i>Bersee mutant A, Bersee mutant C</i>	Worland <i>et al.</i> (1998), Mcintosh <i>et al.</i> (2003)
Rht8	2DL	Hexaploid stock <i>Akakomugi</i>	Worland <i>et al.</i> (1998)
Rht9	7BS	Hexaploid stocks <i>Acciao, Akakomugi, Forlani, Mara</i> , Homologous substitution line <i>Cappelle</i>	Gale and Youssefian (1985), Konzak (1988)
Rht10	4D	Land race <i>Ai-Bian 1</i>	Borner and Mettin (1988), Mcintosh <i>et al.</i> (2003)
Rht11	Unknown	Hexaploid stock <i>Karlik1</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht12	5AL	Hexaploid stock <i>Karcagi 522M7K</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht13	Unknown	Hexaploid stock <i>Magnif 41 Mutant 1</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht14	Unknown	Hexaploid stock <i>Castelporziano</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht15	Unknown	Tetraploid stock <i>Durox</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht16	Unknown	Tetraploid stock <i>Edmore Mutant 1</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht17	Unknown	Hexaploid stock <i>Chris Mutant</i>	Pepe and Heiner (1975a), Pepe and Heiner (1975b)
Rht18	Unknown	Tetraploid stock <i>Icaro</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht19	Unknown	Tetraploid stock <i>Vic Mutant 1</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht20	Unknown	Hexaploid stock <i>Burt Mutant 860</i>	Konzak (1988), Mcintosh <i>et al.</i> (2003)
Rht 22	7AS	Aiganfanmai (Tetraploid)	Peng <i>et al.</i> (2011)

of the dwarfing genes (*Rht1* and *Rht2*) containing varieties Lerma Rojo and Sonara 64 from CIMMYT, Mexico in 1960's led to quantum jump in the developing world especially Indian subcontinent led to green revolution. The lodging was drastically reduced due to reduced height and response to fertilizers and irrigation was realized. Following which most of the Indian varieties released after 1960s contain these two genes only (Jain 1994). Use of *Rht* genes led to design high yielding and fertilizer responsive genotypes which rule largest area of spring wheat in world (Table 2). However, the yield plateau or slow genetic gain (5-6 tonnes/ha) over a period of more than 50 years is a major bottleneck in further yield gains. The original problem was that the increased levels of nitrogen fertilizer that were applied to increase yield also increased stem height and therefore the tendency to lodge. Reduction of stem height using dwarfing genes conferred an improved tolerance of higher levels of nitrogen.

Although there is array of 21 dwarfing genes discovered so far (Table 2.) yet, further reduction in height by using *Rht8* gene or for that matter any dwarfing gene for making triple dwarf types is also not a very feasible choice. As the inability of producing desired biomass to maintain optimum harvest index will result in a compromised source sink relationship, however the different combinations of dwarfing genes could be tried for associated desirable parameters such as improving the elasticity, stem, root and yield.

New plant type (NPT) concept given by Dr Khush at IRRI, resulted in the number of high yielding lines with long panicle that broke the yield barrier of 10 tonnes/ha in rice. The success of NPT revived the similar hope in wheat to break the barrier imposed by PBW 343 followed by HD 2967. Long spike with very stiff and strong stem has always been the trait for designing the new plant type. Singh *et al.* (2007) advocated similar strategy for improving wheat. Wheat production must continue to increase by 2% annually, more particularly in developing world including south-east Asia until 2020 to meet future demands imposed by population and prosperity growth (Yadav *et al.* 2010). It means we need to realize the potential yield of 8 tonnes/ha for which significant changes are required in the plant architecture.

The scope of balancing ear head weight with number of tillers has been utilized to a great extent. The varieties like HD 2009, WH 542 have higher tiller numbers and comparatively lesser ear head weight due to lesser number (15-18) of spikelets per spike while varieties HD 2967 and HD 3086 have compensatory mechanism of high tiller numbers with spikelet number and vice versa. The recently developed variety HDCSW 18 has higher ear head weight with high spikelet number (~25) and profuse tillering but requires a very specific growing environment which requires early seeding under conservation or zero tillage conditions. Therefore, heavier ear heads necessarily needs to be adopted and the spring wheat varieties with higher yield potential have heavier ear heads and are prone to lodging in most parts of world including India.

If we go by the ideotype concept of (Berry *et al.* 2007) we need to develop about 14.6 tonnes of biomass to achieve seven tonnes of grain yield keeping all other phenological traits at optimal level. It means we have to slightly increase the height up to 100 cm or above keeping the number of productive tillers at optimal level and desired increased in ratio of number of grains/spike and 1000 kernel weight which strongly demands to go for better root system architecture (RSA) and culm strength to sustain any change in phenology for increasing yield.

Besides the shoot and above ground factors, the anchorage strength is of equal or rather more importance when we think of such a plant type. The anchorage strength of a plant depended on two characteristics of the root system: the bending strength and the angle of spread of the basal coronal roots (Crook and Ennos 1994). Plants with stronger, more widely spread coronal roots produced larger soil cones during anchorage failure and resisted larger forces. Future breeding for lodging resistance, therefore, should emphasize both on stiffer stem which can provide optimum bending strength and widely spread coronal roots which could hold the plant and prevent root failure.

Root growth angle is negatively correlated with root length density in the top 0-10 cm of soil, but positively correlated with root length density at a depth of 10-30 cm (Oyanagi *et al.* 1993, Nakamoto and Oyanagi 1994). This method thus promises to determine genetic differences in deep-rooting ability, a trait important for drought tolerance. However, more root data from the field need to be compared to establish its reliability. Root pulling strength is also another very practical tool for assessing the lodging tolerance owing to root failure. The spreading angle of root systems (Pinthus 1967), root-clump weight (Thompson 1968), root tensile strength (Manske and Vlek 2002) and root pulling strength (Ortman and Peters 1968) are all related to lodging resistance. Despite its simplicity, this method is rarely used in field studies.

An inheritance pattern of morphological root traits in wheat is still restricted, but indicates they are controlled by a polygenic system. Root systems are largely influenced by additive genes with moderate heritability that may allow breeding progress to be made by selecting for root quantity and depth of penetration (Monyo and Whittington 1970). Over 32% of total phenotypic variability for the root:shoot ratio is conditioned by additive gene effects (Kazemi *et al.* 1979). Although this additive portion of total variance is not especially high, the authors suggest that lines with favorable root: shoot ratios may be obtained by direct selection in early generations of wheat crosses.

Many researchers have found the number of seminal roots to be highly heritable (Key 1973, Tiwari *et al.* 1974). Genetic diversity exists for root traits in bread wheat (Key 1973) and durum wheat (Motzo *et al.* 1992) and considerable variation in the degree of root branching has been found among wheat cultivars (O'Brien 1979). Many landraces and wild species of wheat possess large root systems, but tend to lodge due to their height (Vlek *et al.* 1996, Manske

and Vlek 2002).

The root traits have hardly been under selection for Indian conditions and all the varieties developed so far have been given importance to yield and above ground attributes. Therefore selection for root traits offer an additional and indirect approach for improving the lodging in wheat.

With advent of molecular markers in wheat the traits of interest related to lodging directly or indirectly have been tagged. Keller *et al.* (1999) reported QTLs for lodging resistance in the background of wheat  $\times$  Spelt population. Six QTLs were reported by (Hai *et al.* 2005) for stem strength, culm wall thickness, pith diameter and stem diameter in DH population of wheat. Verma *et al.* (2005) reported seven QTLs located on 1B, 1D, 2B, 2D, 4B, 4D, 6D and 7D chromosomes explain variability for lodging and related traits in wheat.

QTLs being background specific are sometimes hard to be validated on different genetic background but the regions responsible for imparting the strength are mainly structural genes which are conserved by and large across the germplasm.

*Agronomical practices:* The agronomic factors are perhaps most studied and reported factors related to lodging in wheat (Tripathi 1994). Sterling *et al.* (2003) observed that the risk of lodging is strongly influenced by a number of husbandry decisions including variety choice, sowing date, drilling depth, soil fertility and the application of plant growth regulating chemicals. Their influence on lodging risk has been shown to be through their ability to alter crop structure by affecting certain plant characteristics. There are reports that use of N-fertilizer in pockets of Punjab and Haryana is much higher than the required dose as per recommendation by research organization. Overdose of nitrogen induces the succulence in plants making them prone to lodging and disease attack (Tripathi *et al.* 2002). One of the factors is timing and intensity of irrigation and use of N-fertilizer. The time of application of nitrogen has effect on lodging. Low nitrogen at the time of sowing has been reported to significantly reduce lodging in spring wheat while maintaining the same amount of total nitrogen applied (Peake *et al.* 2016).

It is standard practice in northern India to irrigate the fields by flooding method and in majority of cases the fields are over flooded giving more windows to environmental factors to induce lodging. This is mainly done due to timing of electricity supply in rural area.

Lodging if studied in cropping system perspective can reveal some of the most obvious factors. The previous crop has bearing on the inherent fertility levels of fields. The most common cropping systems such as rice-wheat also force to adopt the set of varieties which suit both the seasons and crops (Tripathi *et al.* 2005). There is little window for deviation from the harvesting date of the previous crop for example rice and following crop which is wheat. Adoption of slightly longer duration variety compromises the sowing date of wheat owing to intercultural operations and many other factors. Farmers tend to adopt the proven varieties

which fit this window despite of risk of lodging.

Keller *et al.* (1999) reported that higher seed density will enhance lodging by increasing culm length and decreasing culm diameter as well as total root mass. A lower plant density has been shown to reduce lodging but adjusting the population to such an extent that lower plant density does not compromise the yield per unit area is a matter of further investigation. Practically establishing 200 wheat plants/m compared with 400 wheat plants/m reduced the lodging risk by increasing the strength of the anchorage system by more than 50% and the strength of the stem by 15%. Reducing the plant population as low as 50% may not pay dividend unless the probability of lodging environment is high enough to sustain the crop through compensatory mechanism of more number of productive tillers and higher seed number and higher seed weight (Berry *et al.* 2000).

Conservation agriculture can also provide congenial production environment for identification of higher yielding genotypes and help in further yield realization and minimizing lodging (Gupta *et al.* 2017). But mere identification of higher yielding genotypes will not solve the problem there is requirement of bringing larger cultivated area under the management conditions of CA which is perhaps not possible for different cropping systems followed in wheat growing area.

An approach of developing ideal agronomic package suiting a variety to express its potential to maximum must start along with the developmental phase of variety. The advance progenies (F<sub>5</sub>- F<sub>6</sub> onwards) testing under different management regimes such as plant population, seed rate, fertilizer requirement, irrigation regime and effect of induced lodging. This will filter out the genotypes with specific or general management requirement. For this agronomist have to work in tandem with breeder so that an array of genotypes with differential agronomic package could be developed.

*Growth regulators:* Plant growth regulators (PGRs) have been recommended for reducing the height, stiffen straw, and reduce lodging. However the efficacies of such hormones have been giving differential results and there is differential response of genotypes (Berry *et al.* 2004).

Three major types of PGRs have been introduced including: chlormequat chloride (1960s), ethephon (late 1980s) and trinexapac-ethyl (mid 1990s). In France, Germany and the UK, which have among the largest cereal yields in the world, PGR's are now applied to more than 70% of wheat area (Berry *et al.* 2004). Plant growth regulators (PGRs) have also been used to decrease crop height and further reduce the lodging risk of cereals. Three major types of PGRs have been introduced including: chlormequat chloride (1960s), ethephon (late 1980s) and trinexapac-ethyl (mid 1990s). The larger biomass production associated with increased yield requires greater crop inputs and PGRs are well-recognised as one management strategy to manipulate canopy size to reduce lodging (Pinthus 1974, Berry *et al.* 2000, Berry and Spink 2009). In France, Germany and the UK, which have among the largest cereal yields in the world, PGR's are now applied to more than 70% of wheat area

(Berry *et al.* 2004). Four main classes of PGRs including ethephon (ETH), onium-types (chlormequat, CCC) and second and third generation PGRs the triazoles (such as tebuconazole (TEB)) and trinexapac-ethyl (TE) are used in Australia. These compounds disable the gibberellic acid pathway at different stages of biosynthesis. The most widely evidenced mode of action in the scientific literature for PGRs is in the reduction of plant height when these are applied at early stem elongation in cereals (Berry *et al.* 2004) or rosette formation in canola. Shorter plant height increases crop resistance to lodging and can improve harvestability and possibly grain quality if lodging is associated with increased sprouting. In some instances PGRs have been linked to an increase in stem strength but at the same time also reduce the yield (Tripathi *et al.* 2004).

The use of growth regulators seems akin to use of dwarfing genes but in case if countries like India any extra recommendation to use growth regulators in addition to fertilizers and weedicides will not be very viable choice as considering very large acreage under crop will lead to substantiated input cost which otherwise can be managed by giving the better genotypes to withstand lodging.

**Diseases management:** It is a known fact that diseased plants are more prone to lodging and vice versa. Therefore the inbuilt resistance of important diseases of wheat according to their prevalence in a zone/ area is a prerequisite step before the release of varieties in India. The disease resistance is strictly followed by breeders and monitored by the strong coordinated program of wheat improvement which is one of the best in its kind in world.

The occurrence of outbreak of disease due to bust phase of cycle of resistance in more prominent varieties needs to be tackled with the second line of precaution that is use of chemicals for immediate relief followed by phasing out the variety.

### Conclusion

Lodging is the main problem in further improvement in yield level in wheat even if there are genotypes and potential hybrids which can substantially realize the yield levels of as high as 10 tonnes/ha. The change in plant architecture and modifying production environment for specific need of the genotype to express will be the obvious choice. The use of conservation agriculture for modifying the production environment seems to be plausible but for a limited area. The response to still higher doses of nutrition or enhanced nutrient use by plant for conversion, discovery of bypass channels for nutrient supply and carbon assimilation in sink after lodging, are other prospects wherein the yield reduction could be minimized. The recovery traits after lodging have to be studied at genetic level so that the selection and designing the competent genotype is equally important. The use of field level tools for phenotyping and estimating the recovery parameters is the need of current day. The further compounding of losses after lodging due to diseases, birds, rodents and mammalian pests also needs due consideration especially in Indian conditions. The

development varieties resisting lodging and agronomic package of practice complementing the variety shall be mainstay for Indian conditions. Use of different tools for quantification of lodging extent and losses will give us clear picture of current status and shall help in devising best fit models for tackling the lodging problem.

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