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Lodging: Significance and preventive measures for increasing crop production

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Abstract
Lodging is the displacement of stem and roots of plants from their proper and vertical placement either due to the higher N application, higher wind speed, excessive soil moisture, soil density, storm damage, sowing date or over plant population. Cereals are more prone to the effects of both root and stem lodging. Both type of lodging can occur singly or coincidentally but their effects on crop production overall reduces the health and harvest. The affected plant becomes weaker and tends to earlier seed production. This lowers the crop yield and nutrient content badly. The yield is more affected when lodging occurs at the ear formation stage of the crop. From a strictly mechanical perspective, stem lodged plants are harder to harvest and there is more waste. The selection of semi-dwarf varieties of cereals can minimize the ill-effects of lodging on crop production. Apart from, maintaining proper soil moisture, efficient drainage, minimizing or delaying nitrogen application, and use of growth regulators like CCC are effective towards minimizing the decrease in yield due to lodging.

Keywords: Causes of lodging, Crop production, Lodging, Lodging effects, Preventive measures

Introduction
Lodging is the permanent displacement of stem from its upright position. When stems of normally upright plants fall over and do not return to their upright position, plant is said to have lodged (Pinthus, 1973) [18]. Lodging is also regarded as an abundance disease which restricts the exploitation of yield promoting factor. Although bending at base of the peduncle has also been considered as lodging (Patterson *et al.*, 1957) [16]. Lodging is often not distributed uniformly throughout an affected field but may be scattered over certain sections or spots. Uncertainty in climatic and weather conditions may result in lodging. Lodging, be it a consequence of the use of tall varieties, of inadequate nitrogen management or of unfavorable climate conditions is one of the main barriers on the way to higher mean yields and an enhanced quality of cereal crops (Floss, 2004) [3].
In general, lodging was provoked due to high velocity winds in February, March and April (71, 69 and 72 km/h) coupled with rainfall especially in February and March (143 and 115 mm) at milky stage of the crop (Khakwani *et al.*, 2010) [8]. The situation further aggravated due to soil textural class (silty clay), which created temporarily water logged condition and this favored the root lodging of the crop (Fig 4). Care should be taken while applying the final irrigation to wheat that might be light & at early grain filling stage. Lodging is a most chronic constraint, which is causing tremendous yield reduction in crop plants; therefore, better understanding to control lodging-induced adversities or to enhance lodging resistance in cereals is imperative.

Fig 1: *(a)* Lodging in rice at grain maturity stage, *(b)* Wheat lodging at harvesting stage

Terminology

- **Necking:** Breaking of straw from top joint at maturity.
- **Straggling/dog legging:** Falling over here and there among upright ones.
- **Lodging proper:** Bending of shoot from upright position.
- **Buckling:** Sharp bend at weakest point.
- **Breaking:** Culm divided in parts.

Types of lodging

There are two types of lodging as below –

Stem lodging

It follows bending or breaking of lower culm internodes (Fig 2). Stem lodging occur later in the season as the stalk become more brittle due to crop maturation. Stem lodging may occur when the forces causing deflection exceed the elastic limit of stem. It can be estimated by summing the external forces and simultaneously considering plant height, stem elasticity and stem diameter or thickness. It is restricted to plants that are held tightly by a dry and hard upper soil layer.

Fig 2: Stem lodging

Root lodging

When the entire plant leans or falls over because of root failure, condition is called root lodging (Fig 3). Root lodging also refers to straight and intact culms leaning from crown, involving a certain disturbance of root system. It occurs early in the season. In root lodging the breakage or bending is usually at the crown or upper part of the root system. It occurs in moist soil and the cracks parallel to the planting rows, the side opposite to lodging.

Fig 3: Root lodging

Causes of lodging

- Lodging is induced as a result of inadequate standing power of the crop and adverse weather conditions, such as rain, strong winds, and/or hail, especially in the later part of the crop's growth (Rawson and Macpherson, 2000) [21].
- High levels of nitrogen, high seeding rates, excessive soil moisture and use of tall varieties are the known causes of wheat lodging (Mavi *et al*., 2004) [12].
- Stem lodging may occur when forces causing deflection exceed the elastic limit of the stem.
- Stem lodging may be caused by hail or by previous damage of the culms by insect or by foot rot but its occurrence is induced mainly by storm.
- Root lodging may results from failures in the root system or unfavorable changes in the soil as a support base.
- Root lodging is predominant type of lodging occurring during crucial growth stages and that rain and irrigation, which moisten the soil and thus loosen the anchorage of plants, are its main causal agent.

Mechanical aspect of lodging

Plant is lodged due to wind, rain and hail which exert forces (*p*) operating perpendicularly to culms, thus including a torque which causes bending. Once a culm has been drawn out of its vertical position, the weight of shoot to which it belongs operates as a force (*f*) which will increase the torque. Moreover, this force will grow as bending proceeds.

The external factors which evoke p, especially wind, act predominantly on the head of plants Therefore, torque will affect the whole culm and increase gradually from the top down to basal portion, near the ground, where lever attain its greatest value. Consequently, properties of basal region of culm are decisive for bending. Since the nodes are too rigid to enable bending, this will occur in the internodes, which will permit more bending the longer they are. The total torque (*T*) will be –

$$T = pl_1 + fl_2$$

Where, l_1 and l_2 are the levers of forces p and f

The highest bending resistance moment of the culm should be regarded as straw strength which is often confused with lodging resistance. The property of plant to return its original position after bending, confirms with the definition of elasticity.

Straw strength may be estimated by the torque which will cause stresses of same magnitude as the elastic limit of straw. It is dependent on the value of elastic limit as well as on the rate of increase of stresses with torque *T*.

The relation between torque and stress for a cylindrical rod is –

$$T = S\ (2i/d)$$

Where, i is moment of inertia and d is diameter

The deformation evoked by *S* will be inversely proportional to *E*, which is young modulus of elasticity.

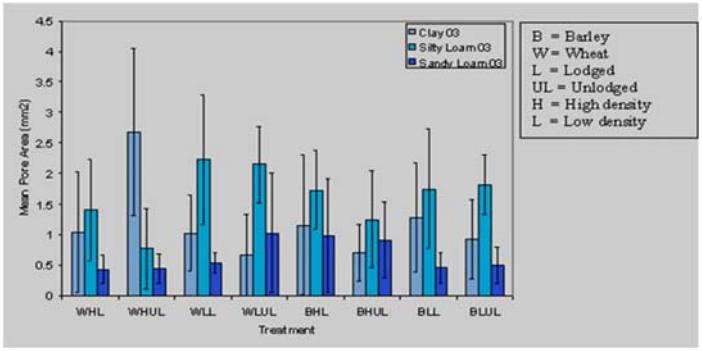

Fig 4: Effect of lodging on mean pore area of wheat and barley in different soil texture

Methods of investigation of lodging

The main methods which have been applied for investigation of lodging are as below –

- Comparison between samples from lodged and from standing areas within same plot
- Comparison of lodging plants in untreated plots with erect plants in CCC-treated plots
- Artificially prevented lodging
- Artificially induced lodging

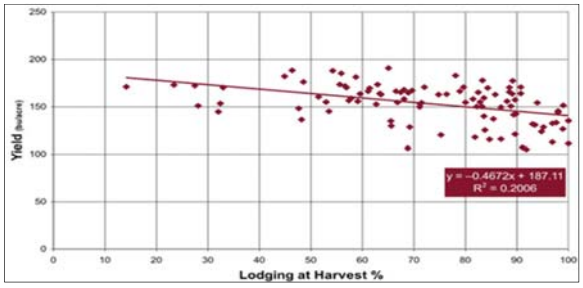

Fig 5: Effect of lodging on crop yield at harvest stage

Effects of lodging

Effects on crop growth

Plants that have lodged may shade other plants, thereby reducing the total amount of photosynthesis that can occur per unit area. When the stalks or stems of plants have broken, transfer of assimilates is restricted or stopped because of damage to vascular bundles.

In plants, that have lodged, respiration continues in the upper parts of plants and depletes the stored carbohydrate reserve in other parts of plant. The weakest plant, following loss of stored carbohydrates become more susceptible to infection by diseases or damage by insects.

Effects on grain yield

Degree of lodging i.e. degree at which culms lean from perpendicular may also vary at different places within field and growth stage at which it occurs. The effect of lodging on grain yield is dependent on its severity and on the time of its occurrence. Lodging close to maturity cannot affect grain yield directly but may cause losses due to its interference with harvest (Fig 5). Artificially induced lodging at heading reduced grain yield by 27-40% whereas yield reduction due to lodging at about soft dough stage surpassed 24% only at one location (Pinthus, 1973) [18]. Khakwani *et al.* (2010) [8] demonstrate that lodging is an important factor in reducing yield up to 38% than that obtained in normal wheat crop. Kelbert *et al.* (2004) reported that lodging can cause yield losses up to 40% if happens during the 10 days after heading. Therefore, it is considered to be the most limiting factor in attaining higher wheat yields (Ransom, 2005; Navabi *et al*., 2006) [20, 14].

Effects on grain yield component

Lodging at heading effects both a number of kernels per head and individual kernel weight and lodging that occur later effects primarily kernel weight. Increase in wheat yield from plots in which lodging had been prevented by application of CCC was associated in increased in number of kernels per spike whereas kernel weight was only rarely and then slightly effected (Pinthus, 1973) [18].

Effect on grain quality

Lodging may cause shriveling of the grain and reduce its test weight. It may reduce milling quality of wheat (Hirano *et al*., 1970) [4] whereas its effect on baking quality seems to be negligible and may sometimes even be advantageous. Sprouting in the heads has also been found to occur frequently in lodged than in standing crop (Kivi, 1961) [9]. Manitoba (2004) [10] observed the increments of 3 to 20% in the grain protein content under lodging conditions, which diminishes the grain malting quality even further. Berry *et al.* (2003) [2] concluded that the lodging in barley is seriously detrimental for brewing purposes. *In situ* seed germination may occur in lodged plants due to conducive environment especially for cultivars with weak seed dormancy. As a result, lodging could cause great losses in both grain yield and quality. In addition, it also causes difficulties in harvest operations, increases demand for grain drying, and consequently results in increased production cost (Hoshikawa *et al*., 1990) [5].

Physiological effects

The most obvious effect of lodging on the plant's physiological processes is its interference with carbohydrate assimilation. This results from a large part of foliage and other photosynthesizing parts being shaded by plants which are leaning or lying on top of them. The heads of low lying plants in a lodging crop may sometimes be completely empty. Whereas those plants lying on top develop normal grain. The protein in cereal grain originates primarily from nitrogen which has accumulated in the foliage prior to heading. Therefore, its absolute amount in the kernels is hardly affected by lodging, which occurs at heading or thereafter. Consequently the, percentage of N, or protein, in the grain of lodged plants may rise due to decrease in carbohydrate accumulation. Lodging which involves culm breakage will also interfere with the translocation of carbohydrates and of minerals**.** In this case the absolute content of N and other minerals in the grain may also be reduced if lodging occurs during heading or early grain development.

It affects flowering, reduces photosynthetic capabilities of the plant and eventually affect carbohydrate assimilation. Under severe condition, lodging interferes with the transport of nutrients and moisture from the soil and restricts mechanical harvesting by taking about twice to harvest a lodged crop than a standing one (Ransom, 2005) [20]

Effects on culm development and tillering

The elongation of the two upper culm internodes, which is not completed until 5-10 days after heading, can be affected by lodging which occurs up to this period. Since these internodes comprise about two thirds of the total culm length any interference with their development may affect straw yield considerably. The straw yield was indeed as much as 25 and 21% lower for lodged wheat and oat plants, respectively, than for supported plants (Mulder, 1954) [13]. Lodging may sometimes promote the development of late tillers, presumably because of the reduction in the competition for the minerals and carbohydrates by the lodging culms. However, these tillers rarely attain normal growth.

Effect on grain harvest

Baumgartner (1969) [1] concluded that in a lodged crop, harvest capacity can be reduced by 25% and the loss of un-threshed heads may be doubled. The moisture content of lodged grain will be higher than of un-lodged grain, which also interferes with the harvest and may increase the expenses for grain drying by 30%.

Incidence of disease in lodging crop

Some environmental factors and several plant characters which promote lodging also improve the growing conditions for rots and leaf diseases. Moreover, these diseases are often favored by the microclimate prevailing with in a lodged crop.

Plant characters associated with lodging

A. Culm character

Culm length-Culm length which comprises the lever of lodging inducing torque, is obviously associated with lodging. An early, short-strawed variety close to maturity will be taller and more prone to lodging than a late, long-strawed variety, which at that time has attained only the late boot or heading stage.

Basal internode-Plants with short stem internodes especially in the lower part of the stem are more resistance to lodging than are plant with long stem internodes. Large stem with thick wall resist greater external lodging forces. The taper ratio of stem is also related to the lodging resistance. This is the ratio of the diameter of the top of the stem to that at the bottom of the stem. The greater the taper ratio, the lower the point of point of fracture, when the defective forces exceed the elastic limits.

Plant height -Within a given plant species tall plants are more likely to lodge than short plants. Since deflection of stem due to external forces is proportional to fourth power of the plant height, a small change in the parameter drastically influences lodging. The elastic limit of short plants is usually greater than that of taller plants but this relationship is not absolute. The plant breeder seeks to develop, not simply short plant, but short plant that can resist lodging.

Anatomical structure-The most marked and significant anatomical features related to lodging resistance was a great no. of vascular bundles. The results regarding the width of sclerenchyma layer are contradictory. This may be due to differences in quantity of assimilating parenchyma embedded in this layer, which was found to be negatively correlated with lodging resistance. The relationship between anatomical feature and lodging resistance may be partly ascribed to effect of lignification on culm rigidity.

Chemical composition-Cellulose and lignin contents in basal internode have been found to be associated with lodging.

B. Root and crown characters

The qualities of the root system affect the anchorage of the plant in the soil and therefore are of major importance in determining resistance to root lodging. Numerical ratings acc. to visual appearances have been used for the assessment of root development. Through such assessments as well as determination of root volume, relationship was established between root development and lodging resistance. Sechler (1961) [22] found a significant correlation ranging from 0.4 to 0.9, between lodging resistance and number of coronal roots per plant or per tiller. He also found positive relationships between lodging resistance and *coronal root diameter* for the different species when a limited number of varieties differing greatly in lodging resistance were compared. A consistent and rather high correlation (0.8) was established in wheat between lodging resistance and the *spread* of *the coronal roots,* expressed as the angle from the perpendicular at which these roots penetrate the ground (Pinthus, 1967) [17].

C. Mechanical properties

- **Straw stiffness** – It refers to flexural rigidity of the culm.
- **Straw strength** – The highest bending moment that the culm is capable of resisting.
- **Breaking strength** – It refers to force required to break a section of certain length of basal culm internodes.
- **Root pulling resistance** – This resistance is the vertical force required to pull out of soil a certain no. of plants and is expressed as force per culm or per plant.

Factors affecting lodging

Light and temperature

Light intensity controls the balance between longitudinal and transverse development of vascular tissue. High intensities block the action of natural gibberellin which promotes both division and elongation of cells. Low light intensity promotes internode elongation and reduces culm wall thickness. Root growth may also be depressed by low light intensity.

An indirect effect on the promotion of internode elongation through increased temperature may be due to its effect on release of soil nitrogen. A significant correlation was found between culm length of barley and temperature during the period from seedling emergence to heading (Pasela, 1967) [15]. Reduction in light integrals (photosynthetic active radiation, PAR) and light quality (red : far-red, R : FR) also increased lodging susceptibility in stem and root traits of wheat (Sparkes and King, 2008; Sparkes *et al*., 2008) [23, 24].

Fertilization

Under excess nitrogen fertility, plants height tends to increase at the expanse of stem strength. Under extreme conditions, lodging may occur very early in the life of plant. Profilic tillering in small grain usually is associated with strong stem-strength and reduced lodging. However under high nitrogen fertility, tillering may be increased excessively and results in

weak stem. When potassium is deficient in the soil, there is less sclerenchyma tissue produced in the stems and this condition causes the stem tissues to be weak. When plants are deficient in phosphorus, all parts of plant grow at lower rates and both stems and roots tend to develop poorly. In this weakened condition, the stems and roots may be less able to resist the forces that cause lodging.

Soil moisture and aeration
When the water table is high, root depth is reduced and lodging may be increased. But, if stems are rapidly elongating, additional water application accelerates their growth and increases water susceptibility. Water stress results in weakened root systems as well as small stems and leaves. It sometimes weakens stem tissues, thereby increasing the possibility of lodging. Poor soil aeration may increase susceptibility to lodging due to effects of respiration inhibition on changes of metabolism which promotes cell elongation.

Plant density
When plants are planted too closely, they tend to elongate rapidly. As a result, stems become lighter and thinner, plants become susceptible to lodging. High plant populations modify the microclimate around plants, which affect lodging.

Soil type
Soil type can influence lodging. For example, the black soil zone has a high percentage of land with 6-8 percent organic matter, which gives a larger reservoir of N for plants to draw on, thereby increasing the risk of lodging.

Manure
On soils where large amounts of manure are applied on a regular basis, (such as from feedlots or dairy operations), there can be a significant buildup of N reserves and thereby increasing the risk of lodging.

Cultivar
Taller varieties tend to have weaker stems and will lodge easier than semi-dwarf varieties, which have stiffer straw. Plant height, stem thickness and straw density can all affect the ability of the plant to resist a lateral force. Changing plant height can have a big influence on lodging.

Pests and diseases
Diseases, such as eyespot foot rot, straw breaker foot rot etc. contribute to lodging. The wheat stem sawfly causes lodging in wheat. As there is no effective chemical control, experts suggest growing a semi solid stemmed variety. Hessian fly can cause lodging and kinking in wheat or barley crops.

Date of planting
When winter cereals are planted too early, vegetative growth may be excessive, thereby increasing the susceptibility of lodging. Excessively late planting of spring grain may increase lodging because rapid growth associated with high temperatures may produce weak stems.

Prevention of lodging
Cultivar selection
The first step to prevent lodging is to select a variety that has short, strong straw. Lodging resistance cultivars have been developed by improving the length of uppermost internodes, thickness of stem wall, quantity and intensity of mechanical tissue, quantity of vascular bundle, content of cellulose and lignin in stem cell wall, the amount of carbohydrate stored in stem, quantity of silicon and potassium and mapping quantitative trait loci for the lodging resistance (Tripathi *et al.*, 2003; Mao-Chun *et al*., 2007) [25, 11].

Fertilizer
Careful monitoring of fertilizer application, especially nitrogen is effective in preventing the lodging. Timing of nitrogen application is particularly important in this context. Dividing the nitrogen into two or three splits and applying as needed by crop plant helps to reduce lodging. The balance of N, P and K in the soil must also be given proper attention. When excess nitrogen is available to plants, it is particularly essential to have sufficient potassium to avoid lodging. It has been suggested to use plant growth retardants and sulphur in order to prevent lodging problem (Ramburan and Greenfield, 2007; Hussain and Leitch, 2007) [19, 6].

Date of Sowing
The probability of the plants being at a growth stage particularly susceptible to lodging, during a period of high frequency of lodging – inducing factors, may sometimes be reduced by a suitable sowing date. For each crop and cultivar there are optimum dates of planting with lodging usually being less when crop is planted at optimum time. When winter cereals are planted too early the vegetative growth may be excessive, thereby increasing susceptibility of plants to lodging.

Method and depth of sowing and row orientation
Deep sowing increases the depth at which the root crown is located and also its length. This may strengthen the anchorage of plants in the soil and thus increases their lodging resistance. Sowing in drill rows in a direction parallel to that of prevailing strong wind may reduce the incidence of stem lodging. This should also be taken into account while the effects are considered of plant row direction on yield due to their influence on light interception. Bed planted genotypes demonstrated over 50% less lodging compared with flat planting provides an evidence that bed planting irrigated spring wheat may be beneficial where chronic lodging occurs (Tripathi *et al*., 2005) [26].

Plant spacing
The establishment of proper and uniform spacing between plants encourages healthy plant growth and permit plants to resist the attack of unpredictable hazards such as storms, heavy rains and diseases. Crowded or sparsely spaced plants tend to lodge. In conclusion, narrow inter row spacing should increase lodging resistance without interfering to say the least with grain yield production.

Irrigation practices
Appropriate irrigation and drainage promote root and above ground plant growth, thus reducing the incidence of lodging. Reduction in early vegetative growth and plant height greatly reduce susceptibility to lodging during and following later irrigation. This suggest advisability of withholding spring irrigation as long as possible, preferably until early boot stage.

Crop rotation
Crop rotation is necessary for the prevention of diseases such as common root-rot, scald, net blotch, and root rot. When a cereal crop is grown in broad leaf crop stubble, such as canola

or flax, the less severe is the disease pressure. Crop rotation practices can be particularly important for irrigation farmers. In the absence of summer fallowing, a crop rotation scheme is useful for the maintenance of soil fertility, disease and weed control. In addition, careful rotations can aid in lowering protein levels in soft white spring wheat and malt barley.

Clipping and grazing

Lodging due to excessive foliage during period of elongation of lower culm internodes may be prevented by clipping and grazing. This should be done before culm elongation has proceeded sufficiently for the epics to be damaged. It seems that in order to secure high grain yields, clipping or grazing should be performed without excessive compaction of soil, and adequate moisture and nutrient supply must be available during subsequent period. However, it is suspected that this method may interfere with attainment of top yield.

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