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Review Article

Harnessing Multi-Scale Phenotyping for Lodging Resistant Wheat: Integrating Traditional and High-Throughput Phenotyping Approaches

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ABSTRACT

Lodging in wheat is rising globally due to climate extremes, causing yield losses of up to 80% based on timing and severity. Lodging poses a major constraint to wheat production in Pakistan, especially in high-input Punjab and Sindh, with climate variability and unseasonal storms causing yield losses up to 40%. Ground-based, aerial, and satellite-based sensing techniques are vital to high-throughput phenotyping for detecting wheat lodging. Ground platforms using RGB (red, green, blue), LiDAR (light detection and ranging), and ultrasonic sensors enable precise measurement of canopy structure. UAV (Unmanned Aerial Vehicle) based imaging enhances coverage and uses RGB, multispectral, and thermal sensors to detect lodging via visual, spectral, and temperature cues, with RGB approaches exceeding 90% classification accuracy. Satellite imaging enables scalable monitoring of lodging through multispectral indices for early stress detection. Combined multi-scale sensing approaches enhance lodging detection efficiency and accuracy in wheat. Each method offers specific advantages and limitations. Field-based phenotyping is cost-effective under natural conditions but lacks scalability. Stem phenotyping provides direct insights into structural strength but is labor-intensive. Simple morphological traits like plant height and internode length indicate lodging risk but are environment sensitive. Wind tunnel testing offers controlled, repeatable evaluations but requires expensive infrastructure. Genetic and molecular screening allows precise, high-throughput selection, while nitrogen response curves link agronomic practices with lodging susceptibility. Together, these methods enhance wheat breeding for lodging resistance. This review systematically integrates and evaluates existing lodging detection approaches and technologies, drawing cross-study insights into their effectiveness and adaptability for improving wheat resilience under current and anticipated climate stresses

Keywords: High-throughput phenotyping, HTP, Lodging resistance, Multi-scale analysis, Phenotypic integration, Wheat improvement

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INTRODUCTION

Lodging is a serious physiological disorder in wheat, defined as the lasting dislocation of stems from their erect position. Its prevalence is increasing worldwide due to mounting climate extremes such as strong winds, storms, and penetrating rainfall, mainly in the regions where lodging-resistant varieties are not broadly adopted. Studies have reported that lodging can lead to extensive yield losses, ranging from 7% to as much as 80%, depending on the wheat growth stage, the severity of the event i.e., strong winds following rains, varietal susceptibility and predominant environmental settings at the time of lodging (Berry *et al.,* 2004).

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Lodging is predominantly widespread in high-input agro-ecosystems (Europe, North America, China, and parts of South Asia) where there is high nitrogen use. Though, low and middle-income nations are also susceptible, expressly under the influence of the changing climate scenario that increases the incidence of heavy rain and windstorms. Lodging remains a serious limitation to wheat production in Pakistan, particularly in the major wheat growing regions of Punjab and Sindh which are categorized by high-input agricultural practices which unintentionally contribute to amplified lodging susceptibility. Besides, climate inconsistency in recent years in the country has exaggerated the incidence of lodging with increased frequency of unseasonal rainfall and windstorms during critical phasic development of wheat. While precise nationwide statistics on lodging-induced yield losses are partial, limited studies advocate that wheat yield can be reduced by 15-35% due to modest to severe lodging events. In some high-input surroundings, such as irrigated fields in Central Punjab, yield losses may surpass 40%, mainly when lodging befalls before grain maturity (Ahmad and Naeem, 2013). As according to Pakistan Meteorological Department. (2022) documents increasing occurrence of windstorms and erratic rainfall in Punjab will cause wheat lodging triggering a potential threat for food security in the country. (Pakistan Meteorological Department, 2022).

This review introduces a novel framework integrating traditional field assessments with high-throughput phenotyping tools-such as UAVs, LiDAR, and multispectral imaging-for multi-scale evaluation of lodging resistance in wheat. By synthesizing data across platforms, it enables earlier, more precise, and scalable detection, supporting climate-resilient breeding and precision management.

THE INTEGRATION AND USE OF NOVEL APPROACHES

The integration and use of novel approaches for detecting lodging resistance in wheat involves both high-throughput phenotyping (HTP) and non-high-throughput phenotyping (NHTP) methods. The side-by-side comparative Table 1 summarizing the key features of both approaches.

HIGH THROUGHPUT PHENOTYPING APPROACHES

Lodging can occur unexpectedly imaging is not frequent enough due to timing and occurrence. Most models fail to forecast lodging before it occurs, only detecting it post-collapse. In plant breeding, HTP phenotyping offers a non-destructive and non-invasive method for measuring complex genetic traits-such as lodging resistance-thereby accelerating the rate of genetic gain. These approaches include ground-based sensing, aerial/drone-based sensing and satellite-based sensing (Figure 1).

Ground based sensing

Ground-based sensing techniques have become vital gears of HTP phenotyping platforms for detecting lodging in wheat. These approaches exploit a variety of sensors-such as RGB imaging, LiDAR and ultrasonic sensors-mounted on mobile platforms including carts, tractors or phenomobiles. Situated near the crop canopy, these systems permit the detection of high-resolution and precise phenotypic data. They deliver comprehensive measurements of key structural traits such as canopy height, stem inclination and biomass distribution, which serve as critical indicators of lodging under field conditions. On ground-based fixed platforms many researchers highlighted the malleability and suitability of RGB imaging. A solid association originated with traditional visual scoring approaches by applying RGB-derived canopy cover analysis, lodging severity was assessed by measuring discounts in green pixel area by Singh *et al.* (2016). By discharging laser pulses to estimate the distance among the sensor and crop surfaces, LiDAR-obtained point clouds and height maps which offer the fitness to capture inclusive 3D structural evidence of the crop canopy. Gracia-Romero *et al.* (2019) utilized a ground-based LiDAR platform to monitor wheat under lodging stress and verified that discounts in canopy height and augmented inconsistency in height were reliable pointers of lodging severity.

The ultrasonic sensors offer a non-invasive, cost-effective ground-based method for detecting lodging in wheat by emitting high-frequency sound waves and estimating plant height based on the echo time delay from the crop canopy. Kipp *et al.* (2014) employed tractor-mounted ultrasonic sensors to monitor canopy height variations under different management practices and found that significant deviations in height linked well with visually judged lodging harshness.

Aerial/drone-based sensing

Aerial or drone-based sensing has become an influential HTP approach for detecting and monitoring lodging in wheat, offering high spatial and temporal resolution across large field trials. Commonly employed methods include UAV-based RGB imaging, multispectral imaging, and thermal imaging. For lodging detection in wheat, Shahzad *et al.* (2021) used UAV-based RGB imagery approach by regulating performance sample size and metrics between un-lodged and lodged fields and found that this method openly and precisely approximates lodging severity.

Table 1. The side-by-side comparative key features of HTP and Non-HTP approaches

Key features	Non-HTP Approaches	HTP Approaches
Automation level	Hand-operated measurement	Extremely machine-driven
Speed	Slow and labor-intensive	Speedy and efficient
Scale	Small-scale application	Large-scale application
Precision	Subjective bias	Objective unbiased
Cost	Lower initial but high labor cost over time.	High initial cost but cost-efficient in the long run.
Data	Manual, small datasets and destructive sampling	Automated, massive datasets, non-destructive sampling
Application in breeding	Constricted throughput	Wide based throughput
Key limitations	Low measurability, human error, limited trait multifariousness.	High initial cost, data complexity, requires technical skillfulness.

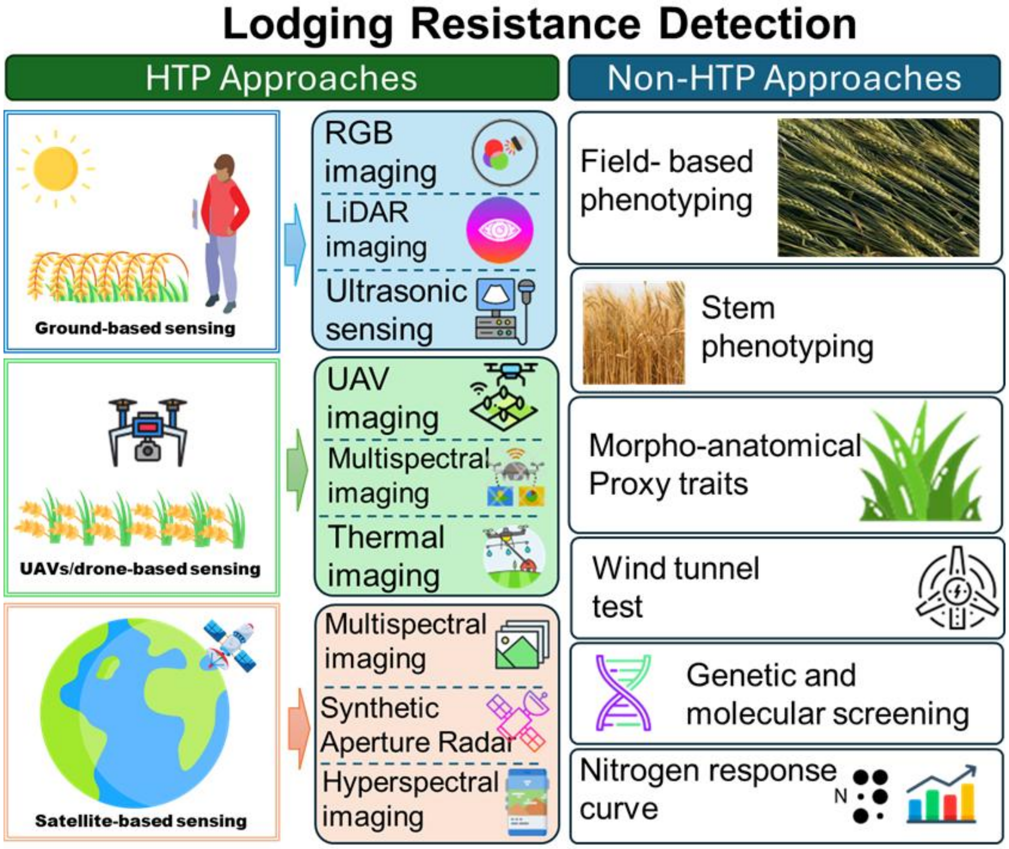

Figure 1. HTP-based approaches and non-HTP-based approaches and scoring system for detecting lodging resistance in wheat.

By taking reflectance pictures across multiple spectral bands, multispectral imaging has become a valued tool for lodging detection among HTP approaches as it proposed enhanced sensitivity to structural and physiological disparities in the crop canopy. In many findings multispectral imaging approach proved as a scalable, prompt and non-destructive strategy for lodging detection in wheat. For instance, Tattaris *et al.* (2016) conducted wheat breeding trials to evaluate biomass and canopy temperature and found lodged-prone wheat lines in the form of spectral reflectance decorations by smearing multispectral imaging. Lodging elevated canopy temperatures which eventually lessens stomatal conductance by unsettling airflow which can be measured by thermal infrared sensors. As thermal imaging capture canopy temperature differences allied with stress and transformed transpiration therefore, this approach offers latent for lodging detection in wheat. For example, Deery *et al.* (2016) suggested its worth in detecting physiological deviations to record canopy temperature depression as an indicator of stress connected with the lodging.

Satellite based imaging

Satellite-based imaging is an important and scalable tool for observing lodging in precision agriculture and wheat phenotyping which deliver results in the form of spatial and temporal patterns across extensive coverage with repeated instances. As a consequence of lodging thermal traits, canopy reflectance, structural consistency are altered that can be sensed using satellite-derived spectral indices (Normalized Difference Vegetation Index-NDVI, red-edge NDVI, canopy temperature-CT and vegetation index). Satellite based imaging comprises multispectral imaging, synthetic aperture radar and hyperspectral imaging.

Multispectral imaging systems (Onboard Sentinel-2 and Landsat 8) also likeminded for large-scale crop monitoring approach as it detect reflectance in the visible and near-infrared electromagnetic band area by high reexamine occurrence, realistic spatial resolution with free openness. However, its major drawback is its incomplete spectral depth imaging which may force the detection of delicate lodging linked physiological dissimilarities. By using multispectral data and deep learning techniques, Li *et al.* (2023) confirmed effective lodging detection in wheat.

Synthetic apertures radar such Sentinel-1 and 2 is aapproach which provide consistent structural sensitivity and sends microwave signals to perceive crop structural traits useful for lodging detection. Even with these benefits, its data often exhibits minor spatial resolution and needs multifaceted clarification, which may obligate its functional usage. For illustration, Veloso *et al.* (2017) indorsed that chronological declines in vegetation indices could serve as indicators of lodging in wheat by using the potential of Sentinel-2. Conversely, hyperspectral imaging captures reflectance across hundreds of narrow spectral bands, allowing detailed biochemical and structural analysis. This approach is accessible by emerging satellite tasks (PRISMA and EnMAP) which supplies high spectral sensitivity and is feasible for initial detection of lodging stress. Yet, its broader application is currently constrained by partial satellite openness, high preprocessing strains and large data volumes.

Recent studies by Fiorani *et al.,* 2023 have validated the utility of these platforms in agricultural monitoring, highlighting their potential in phenotyping, stress detection and crop condition valuation including lodging resistance under variable environmental settings. Satellite imaging methods should be evaluated more critically by accounting for cost, resolution, and technical skill requirements. Free platforms (Sentinel-2 and Landsat) offer moderate-resolution multispectral data suitable for broad-scale monitoring but may lack the spatial detail needed for plot-level analysis. In contrast, commercial satellites (World View and Planet Scope) provide high-resolution imagery but are often costly, limiting accessibility for low-budget breeding programs. Moreover, effective data utilization demands expertise in remote sensing and GIS. Thus, selecting a satellite imaging approach requires careful consideration of financial resources, resolution needs, and available technical capabilities.

NON HTP BASED APPROACHES AND ITS SCORING SYSTEM

Table 2 presents the non-HTP-based approaches and their scoring systems for detecting lodging resistance in wheat. These approaches include field-based phenotyping, stem phenotyping, morpho-anatomical proxy traits, wind tunnel testing, genetic and molecular screening and nitrogen response curve.

Field-based phenotyping

In wheat lodging detection, field-based phenotyping entails visually assessing lodging traits within elected plots to assess various genotypes under natural field conditions. Lodging is frequently measured by thresholds and an angle scale for lodging sternness. The advantages of this method comprise its cost-effectiveness, ease and capability to assess wheat under actual environmental pressures (wind and rain) making it valued for breeding plans and offering a complete view of lodging conduct. Nevertheless, disadvantages include probable disparity due to rough field circumstances, bias in visual scoring and partial repeatability across environments and seasons. As a result, genotype-by-environment interactions can obscure genuine genetic resistance. This method is labor-intensive mainly in extensive trials. Notwithstanding these challenges, the fact remains that field-based phenotyping proved to be a vital approach for confirming genetic data in wheat lodging detection studies.

Stem phenotyping

Stem phenotyping offers the benefit of being directly apropos and useful to the biomechanical mechanisms of lodging, permits for resistance assessment at the organ level and highlights the appraisal of structural traits (solidness, diameter and thickness) which enhance the crop's resilience to wind and rain. Greater bending strength and solid stem internodes is directly proportional to improved lodging resistance that helps for effective selection for breeding programs. Operose procedures and low scalability are the major constraints of this approach when applied to huge populations. Even so, this type of phenotyping is still a vital approach for the improvement of structural lodging resistance in wheat.

Morpho-anatomical proxy traits

Morpho-anatomical proxy traits, such as basal internode length and plant height are imperative yard sticks used in lodging detection in wheat because these traits assist the breeders for assessing a plant structural integrity deprived of multifaceted equipment. For instance, shorter internodes and reduced plant height lower the center of gravity, thicker stem walls and organized vascular bundles that strengthen mechanical support.

Table 2. Non-HTP-based approaches, their scoring systems, tools and stages for detecting lodging resistance in wheat.

<table>
<tr><th>Sr No</th><th>Non HTP</th><th>Scoring systems</th><th>Tools and Stages</th><th>Reference</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">Field-based phenotyping</td><td>(i)-Plot definition
<table>
<tr><th>Scale</th><th>Description (%)</th></tr>
<tr><td>0</td><td>0 (No lodging)</td></tr>
<tr><td>1</td><td>1-10 (Traces)</td></tr>
<tr><td>2</td><td>11-25 (Mild)</td></tr>
<tr><td>3</td><td>26-50 (Moderate)</td></tr>
<tr><td>4</td><td>(51-75 (Severe)</td></tr>
<tr><td>5</td><td>76-100 (V. severe)</td></tr>
</table>
(ii)-Lodging threshold
<table>
<tr><th>Area (%)</th><th>Class</th><th>Interpretation</th></tr>
<tr><td>0-10</td><td>Resistant</td><td>Suitable for commercial release</td></tr>
<tr><td>11-25</td><td>Moderately Resistant</td><td>May be suitable in favorable zones</td></tr>
<tr><td>26-50</td><td>Moderately Susceptible</td><td>Further improvement needed</td></tr>
<tr><td>>50</td><td>Susceptible</td><td>Poor candidate for breeding</td></tr>
</table>
</td><td>=Visual observations
=Zadoks 60-89</td><td>Berry *et al.*, 2000</td></tr>
<tr><td>(iii)-Inclination angle scale
<table>
<tr><th>Score</th><th>Angle</th><th>Description</th></tr>
<tr><td>1</td><td>0°</td><td>No lodging</td></tr>
<tr><td>3</td><td>~30°</td><td>Slight inclination</td></tr>
<tr><td>5</td><td>~45°</td><td>Moderate lodging</td></tr>
<tr><td>7</td><td>~60-70°</td><td>Heavy lodging</td></tr>
<tr><td>9</td><td>~90°</td><td>Completely lodged</td></tr>
</table>
</td><td>=Protractor or Angle gauge
=Zadoks 60-89</td><td>Fischer *et al.,* 1987</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Stem phenotyping</td><td>(i)-Stem bending strength
<table>
<tr><th>Score</th><th>Value (N)</th><th>Resistance</th></tr>
<tr><td>1</td><td>> 20 N</td><td>V. Strong</td></tr>
<tr><td>2</td><td>15-20 N</td><td>Strong</td></tr>
<tr><td>3</td><td>10-15 N</td><td>Moderate</td></tr>
<tr><td>4</td><td>5-10 N</td><td>Weak</td></tr>
<tr><td>5</td><td>< 5 N</td><td>V. Weak</td></tr>
</table>
</td><td>=Manual bending tester or Universal testing machine
=Zadoks 65-75</td><td>Berry *et al.,* 2000</td></tr>
<tr><td>(ii)-Stem diameter
Larger diameter = more mechanical strength = better lodging resistance
Diameter >4.5 mm= stronger</td><td>=Digital vernier caliper or micrometer screw gauge
=Zadoks 65-75</td><td>Shah *et al.,* 2017</td></tr>
</table>

<table>
<tr>
<td></td>
<td></td>
<td>(iii)-Stem wall thickness
<table>
<tr><td>Score</td><td>Stem Wall Thickness (mm)</td><td>Resistance</td></tr>
<tr><td>1</td><td>> 2.5</td><td>Highly resistant</td></tr>
<tr><td>2</td><td>2.0-2.5</td><td>Resistant</td></tr>
<tr><td>3</td><td>1.5-2.0</td><td>Moderately resistant</td></tr>
<tr><td>4</td><td>1.0-1.5</td><td>Susceptible</td></tr>
<tr><td>5</td><td>< 1.0</td><td>Highly susceptible</td></tr>
</table>
</td>
<td>=Digital caliper or microscope with image analysis for precise thickness
=Zadoks 70-99</td>
<td>Berry <i>et al.,</i> 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(iv)-Stem solidness
<table>
<tr><td>Score</td><td>SSI</td><td>Type</td><td>Resistance</td></tr>
<tr><td>1-2</td><td>>0.70</td><td>Very solid</td><td>V. High</td></tr>
<tr><td>2-3</td><td>0.60-0.70</td><td>Moderately solid</td><td>High</td></tr>
<tr><td>3-4</td><td>0.50-0.60</td><td>Medium solidity</td><td>Moderate</td></tr>
<tr><td>4-5</td><td>< 0.50</td><td>Week stem</td><td>Low</td></tr>
</table>
</td>
<td>=Razor blade, ruler, magnifier
=Zadoks 37-49</td>
<td>Kongraksawech <i>et al.,</i> 2020</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(v)-Core sampling
<table>
<tr><td>Trait</td><td>Description</td><td>Ideal Threshold</td></tr>
<tr><td>Root length density</td><td>Root length soil volume^{-1}</td><td>> 1.5 cm cm^{-3} in top 20 cm = stronger anchorage</td></tr>
<tr><td>Root biomass</td><td>Dry weight volume^{-1}</td><td>> 0.1 g/100 cm^3 soil</td></tr>
<tr><td>Root penetration depth</td><td>Max root depth</td><td>> 60 cm</td></tr>
<tr><td>Root surface area</td><td>Calculated from washed roots</td><td>Larger = better soil interaction</td></tr>
</table>
</td>
<td>=PVC tube, Soil auger, Rubber hammer, Spade, Ruler, Drying oven and digital balance
=Zadoks 45-75</td>
<td>Berry <i>et al.,</i> 2000</td>
</tr>
<tr>
<td>3</td>
<td>Morpho-anatomical proxy traits</td>
<td>(i)-Basal internode length
Distance between nodes (especially 2nd to 4th internode)
< 15 cm exhibit better resistance</td>
<td>=Ruler
=Zadoks 30-39</td>
<td>Kongraksawech <i>et al.,</i> 2020</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ii)-Plant height measurement
≤ 80-90 cm</td>
<td>=Measuring tape
=Zadoks 80-89</td>
<td></td>
</tr>
</table>

<table>
<tr>
<td>4</td>
<td>Wind tunnel testing</td>
<td>(i)-Wind tunnel
<table>
<tr><td>Score</td><td>Description</td></tr>
<tr><td>1</td><td>No lodging, perfectly upright</td></tr>
<tr><td>3</td><td>Slight bending, minimal angle</td></tr>
<tr><td>5</td><td>Moderate leaning, 45°or less</td></tr>
<tr><td>7</td><td>Severe lodging, close to flat</td></tr>
<tr><td>9</td><td>Complete prostration, stem breakage</td></tr>
</table>
</td>
<td>=Anemometer
=Zadoks
65-75
80-85
90 plus</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Genetic & molecular screening</td>
<td>(i)-MAS
<table>
<tr><td>Trait</td><td>Common QTLs/markers</td><td>Resistance threshold</td></tr>
<tr><td>Plant height</td><td>Rht-B1b, Rht-D1b</td><td>70-90 cm</td></tr>
<tr><td>Culm diameter</td><td>QTLs on 2A, 3B, 5D</td><td>> 3.5 mm</td></tr>
<tr><td>Stem wall thickness</td><td>Xgwm389 (3A), Xgwm 533 (4D)</td><td>> 1.0 mm</td></tr>
<tr><td>Root plate spread</td><td>QLrg.niab-6A, QLrg.cim-3B</td><td>> 4 cm</td></tr>
<tr><td>Internode strength</td><td>QTLs on 1B, 2D, 6A</td><td>Break force>25 N</td></tr>
</table>
</td>
<td>=Tissue collection tools, deep freezer (-80°C), Centrifuge, DNA extraction kit, Gel electrophoresis apparatus, Gel imaging system, PCR machine
=Zadoks
30-39
41-59
70-85</td>
<td>Pinera *et al.,* 2016, Mohebodini *et al.,* 2020</td>
</tr>
<tr>
<td>6</td>
<td>Nitrogen response curve</td>
<td>(i)-Nitrogen response
<table>
<tr><td>Score (%)</td><td>N-relation</td></tr>
<tr><td>1-2 (<10%)</td><td>Balanced N, short stem</td></tr>
<tr><td>3-4(10-30%)</td><td>Moderate excess N</td></tr>
<tr><td>5-6(30-50%)</td><td>Sub-optimal N partitioning</td></tr>
<tr><td>7-8(50-80%)</td><td>Overgrowth, weak walls</td></tr>
<tr><td>9(>80%)</td><td>Excess N, delayed senescence</td></tr>
</table>
</td>
<td>=SPAD, green seeker
=Zadoks
30-39
55-75</td>
<td>Sylvester *et al.,* 2012</td>
</tr>
</table>

Therefore, upgraded lodging resistance is directly linked with these traits. In early filial generation selection, these traits are valuable due to their applicability and architectural worth. However, subjective visual valuation, trait appearance environmental inconsistency and latent inability to totally characterize complex dynamics of lodging are their limitations. Yet, for assessing lodging resistance in wheat, this approach delivers a cost-effective, biologically relevant method and simple indicators of lodging risk.

Wind tunnel testing

Regardless of changing or erratic environmental settings, this precise approach has the capacity to deliver reproducible and objective data on lodging resistance by simulating wind forces on crops. By exposing wheat plants to control wind speeds in semi-field states or laboratories, this approach can rightly appraise, stem bending, root anchorage resistance and lodging thresholds. Merging it with field valuations it provides a more accurate picture of lodging resistance as it misses the possible variances between simulated and natural lodging setups. However, expensive equipment, infrastructure requirements, technical expertise and limited scalability for large breeding programs expresses its downsides. Its practicality can be improved by evolving portable structures or affiliating with research organizations.

Genetic and molecular screening

Lessening the need for wide phenotyping for lodging detection of large population, the genetic information procedures (marker-assisted selection, genomic selection, and genome-wide association) permit faster and more active assessment with high precision at early generation selection. Additionally, it can pyramid multiple favorable alleles, empowers breeders to hasten genetic gains by lessening reliance on environmental discrepancy. Even with these benefits, this method has restrictions, such as high genotyping costs, the prerequisite for advanced infrastructure, specialized know-how, the shortage of well-characterized markers for all lodging-linked traits and marker performance may differ across different field conditions. For integrating lodging resistance into conventional wheat breeding efforts, this approach continues to be vigorous and scalable.

Nitrogen response curve

This approach is mainly applicable in modern agronomic systems where nitrogen management directly impacts both yield and lodging risk because this suggests the answer to question that how varying nitrogen levels effect plant growth and structural steadiness. Breeders can identify genotypes that retain stem strength even under excessive fertilization by plotting grain yield or plant height against increasing nitrogen application rates. Such information is yard stick for breeders targeting to develop lodging resistant wheat cultivars appropriate to industrialized agriculture as this method contributes to the formulation of fertilizer policies that optimize yield while minimizing lodging. This structural approach is conducted under controlled field conditions using multiple nitrogen treatments with consistent seeding rates, irrigation, pest control and incorporation of both susceptible and resistant varieties. A suitable experimental design, such as a randomized complete block design, minimizes environmental variation. Phenotypic traits like plant height, stem strength, and lodging incidence are measured, and response curves are developed by plotting nitrogen levels against these traits to identify critical thresholds influencing lodging risk. Nitrogen response curves serve as a useful bridge between agronomic practices and genetic selection. Their utility could be enhanced by integrating them with high-throughput phenotyping tools, mechanical trait analysis, and crop modeling. Regarding drawbacks, when this approach is replicated across diverse environments, multiple nitrogen trials are costly, laborious and time-consuming and environmentally mutable (soil heterogeneity, wind pressure, root anchorage and density) may be compromised which can obscure true genetic variation in lodging resistance.

Additionally, in smallholder settings, the affordability of advanced lodging detection tools are restricted by high costs and technical intricacy. Though effective, these methods often depend on institutional backing. Instead, basic field assessments offer a low-cost, practical solution despite lower accuracy. Economic accessibility can be improved through shared platforms, free satellite data, and partnerships with research organizations, supporting broader adoption in smallholder-oriented breeding efforts.

INTEGRATED APPLICATION OF HIGH-THROUGHPUT AND CONVENTIONAL PHENOTYPING FOR LODGING RESISTANCE IN WHEAT

The challenge of accurately assessing lodging resistance in wheat has encouraged the integration of HTP systems with traditional, low-throughput approaches. HTP technologies including drone-based RGB imaging, LiDAR, multispectral, and thermal sensors enable researchers to monitor crop structural and physiological changes at large scale, with high temporal precision. These approaches are particularly valuable for identifying spatial variability in traits like canopy height and stem angle, which are key indicators of lodging risk. For instance, UAV-based inaging followed by lodging mapping has demonstrated success in distinguishing lodged plots from healthy ones under field conditions (Zhao *et al.*, 2020). Similarly, ground-based LiDAR systems have been shown to detect subtle shifts in plant architecture before collapse occurs, offering non-invasive and repeatable alternatives to manual scoring (Rebetzke *et al.*, 2019). However, despite their scalability and automation, HTP methods alone may not capture the complex biomechanical and genetic foundations of lodging, especially in early-stage or small-scale breeding programs aimed at the development of lodging resistance in wheat.

This is where conventional, non-HTP methods complement high-tech platforms. Visual field assessments, stem mechanical testing, and morpho-anatomical trait measurement remain essential tools, especially for confirming resistance at the organ or whole-plant level. Traits such as internode diameter, stem wall thickness, and basal bending strength offer critical insights into the structural resilience of genotypes, often serving as proxies for deeper genetic traits.

Shah *et al.* (2019) emphasized that combining HTP platforms with field-based observations strengthened the robustness of selection, particularly in environments with unpredictable weather patterns or soil heterogeneity. Moreover, integrating phenotypic data from both approaches with genomic tools like marker-assisted or genome-wide association mapping enhances precision breeding by linking observable traits to quantitative trait loci (QTLs). For sure, this hybrid strategy leverages the strengths of both scales: HTP enables rapid screening across diverse populations, while traditional methods deliver targeted validation of traits, ensuring that breeders can reliably select lodging-resistant cultivars under both controlled as well as natural field conditions (Singh *et al.*, 2019; Chawade *et al.*, 2019).

CONCLUSION

Integrating advanced sensing technologies with conventional phenotyping and genetic tools is indispensable for refining lodging detection and resistance in wheat. While each approach-from ground-based sensors to UAV and satellite imaging, and from stem trait analysis to nitrogen response curves-has discrete strengths and restrictions, their combined application improves accuracy, scalability, and resilience in wheat breeding programs. For effective adoption, investment in sensor technologies, data infrastructure, and capacity building is essential. Integrating HTP in this way enhances the accuracy and speed of selecting lodging-tolerant genotypes, thereby boosting genetic gains and resilience in wheat breeding programs. As climate variability increases the risk of lodging, particularly in vulnerable regions like Pakistan's Punjab and Sindh, these integrated strategies are vital for sustaining wheat productivity and developing climate-adaptive lodging resistant wheat varieties.

AUTHOR CONTRIBUTIONS

MZ, JA, SR conceptualized and drafted the manuscript. SM, AA, SA, MN, MHT, MO, MMJ and RS conducted the literature review, contributed to editing and refining the manuscript**.**

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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