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High-Density Planting Combined With Lodging-Resistance Traits Improves Field Performance in Maize

Jinhua Cheng, Wei Wang
Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China
Corresponding email: wei.wang@jicat.org
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Abstract High-density planting is an important means to increase the yield per unit area of corn, which is conducive to making full use of light and heat resources and optimizing the photosynthetic efficiency of the population. However, the consequent risk of lodging has significantly increased, seriously affecting the field performance, grain filling and mechanical harvesting efficiency of corn. This study systematically explored the synergistic relationship between high-density planting and lodging resistance traits. It sorted out the related genetic, physiological basis and breeding progress from aspects such as stem strength, root structure and plant type regulation. Through the analysis of the research progress of key lodging resistance genes and QTL, it clarified the important role of lodging resistance traits in high-density breeding. And an integrated path of molecular marker-assisted selection and compact plant type cultivation was proposed. Field cases taking Northeast, North China and Southwest China as examples show that the collaborative optimization of germplasm traits and cultivation management measures is conducive to achieving high-density and stable yields. This study aims to establish a sustainable and mechanized corn production system and promote the application of smart agriculture in anti-lodging planting.
Keywords Maize; High-density planting; Anti-lodging property; Corn field performance; Breeding strategy

1 Introduction

Planting corn more densely is a path that countries have had to take in recent years in order to increase the yield per unit area. The reason behind this approach is actually not complicated - there is not enough land, but the demand for food is still on the rise. Against this backdrop, high-density planting has gradually become the "default option" for increasing production. Especially with the improvement of breeding levels and field management techniques, more and more corn varieties can withstand the pressure of dense planting, and the suitable density in various regions is also quietly increasing. In a country like the United States, the planting density has increased from 55 000 plants per hectare to nearly 100 000 plants over the past few decades, and the output has also doubled accordingly. China and other major producing countries are also following a similar path (Ren et al., 2025). However, in fact, the ability to adapt to high density does not only rely on "planting well", but also makes significant contributions from hybrids - structural features such as short stalks, upright leaves, and deep roots not only resist compression but also make more efficient use of water, fertilizer and light.

However, things are not that simple. It's good to plant densely, but once management is inadequate or the varieties are not resistant to being squeezed, problems will arise immediately when competition breaks out. When there is insufficient light and the plants cannot compete with water and fertilizer, they start to "grow taller", resulting in elevated panicle positions and soft stems. When a storm came, some fields collapsed before they could be harvested. Lodging is not merely about reducing production. Mechanical harvesting has also become a problem, delaying agricultural work and easily affecting the quality of grains. Especially for those hybrid varieties with overly tall plants and insufficiently hard stems, they are more prone to problems under density pressure. At this point, relying solely on one breeding or a single measure is not sufficient. Efforts should be made simultaneously from both the breeding and cultivation levels.

This study aims to systematically evaluate how the combination of high-density planting and lodging resistance traits improves the field performance of corn, review the genetic, physiological and agronomic factors affecting lodging under dense planting conditions, assess the latest progress in enhancing lodging resistance breeding and management practices, and explore its significance for sustainable yield increase and large-scale mechanized production. By integrating existing knowledge and highlighting practical strategies, this study aims to provide references for breeding programs and field management, and promote the development of high-yield and lodging resistant maize systems.

2 Genetic and Physiological Basis of Lodging Resistance in Maize

2.1 Stem strength and the development mechanism of mechanical tissue

Not all corn lodging problems lie in the roots; the strength of the stems is often the key. Physical indicators such as stem diameter, bending resistance, and cortical puncture resistance are basically inversely proportional to the lodging rate (Manga-Robles et al., 2021). However, when it comes to what can enhance these strengths, the core lies in the development of mechanical tissues, such as the condition of thick-walled tissues and vascular bundles. Especially the thickness of the cell wall, the amount of cellulose content, the arrangement structure of the cell wall, etc., will all affect whether the stem has a "waist" or not. The lower internodes are a key area. If the lignin accumulates insufficiently here, the stem bark's resistance to penetration will be poor, and problems are more likely to occur in stronger winds (Li et al., 2022). Nowadays, many breeding and management techniques are targeting this point, with the aim of rapidly depositing dry matter and synthesizing more lignin in the internodes at the base, making the stems more "tough".

2.2 Influence of root architecture and rooting depth on lodging resistance

Ultimately, whether corn can stand steadily or not, its roots also account for half of the sky. Especially in a densely planted environment, if the roots are not firm, it will be troublesome if they fall over during wind and rain (Zheng et al., 2023). Some traits stand out in this regard, such as a wide enough root crown, a large root Angle, thick pillar roots, and deep roots. All these help the roots to better "grasp the ground". Some studies have specifically evaluated the stability of roots by the ratio of superweight to vertical tensile strength (Xue et al., 2020). However, it is not the case that being thick and strong is necessarily good. Some detailed traits, such as root hair density and the distribution hierarchy of roots, also have an impact on lodging resistance, and these characteristics cannot be easily observed with the naked eye. Now that the planting density has increased, it is even more necessary to consider how to adjust the structure of the roots, such as strengthening the embryo roots and increasing the dry matter in the underground part. Only in this way can the plants be stabilized without affecting nutrient absorption (Zhang et al., 2023).

2.3 Advances in the identification of key lodging-resistance genes and QTLs

Research has been conducted for many years, and many QTLS and candidate genes related to lodging resistance have been located (Sun et al., 2020). On the stem side, it is mainly the mechanism of cell wall biosynthesis at work, such as genes involving membrane steroid-binding proteins, pectin methylesterase, and cell cycle regulation, which all have regulatory effects on how cells grow and divide (Yang et al., 2024). In terms of roots, the sites that regulate the number of root nodes, root angles and support root development have also been identified. Quite a few genes have "part-time" roles both above and below ground, that is, they are pleiotropy. However, the genetic structure of these traits is complex, with many superior interactions, and they are quite sensitive to the environment. Ultimately, integrating those alleles that are conducive to strong stems and stable roots is still the most direct breeding breakthrough to achieve lodging resistance under close planting conditions.

3 Effects of High-Density Planting on Maize Physiological and Ecological Traits

3.1 Changes in canopy structure and photosynthetic efficiency

A closed canopy is not necessarily a bad thing. Once the planting density is increased, indicators like LAI naturally follow suit, the interception of photosynthetically active radiation (PAR) also increases, and the overall biomass of the population increases (Figure 1) (Tian et al., 2022). However, the lower leaves were not so lucky. The shading problem was obvious. Light couldn't penetrate and the photosynthetic efficiency dropped sharply. Some modern breeding ideas are quite interesting, such as the "intelligent canopy" approach, where the upper leaves stand upright and the lower leaves spread flat, allowing light to penetrate more reasonably. The effect is particularly obvious when planted densely (Tian et al., 2024). However, it should be said that the density cannot be increased too much either. Otherwise, PAR cannot reach the lower layer, the chlorophyll content will decrease accordingly, the photosynthetic efficiency will drop, and the final yield will also be blocked (Yan et al., 2024).

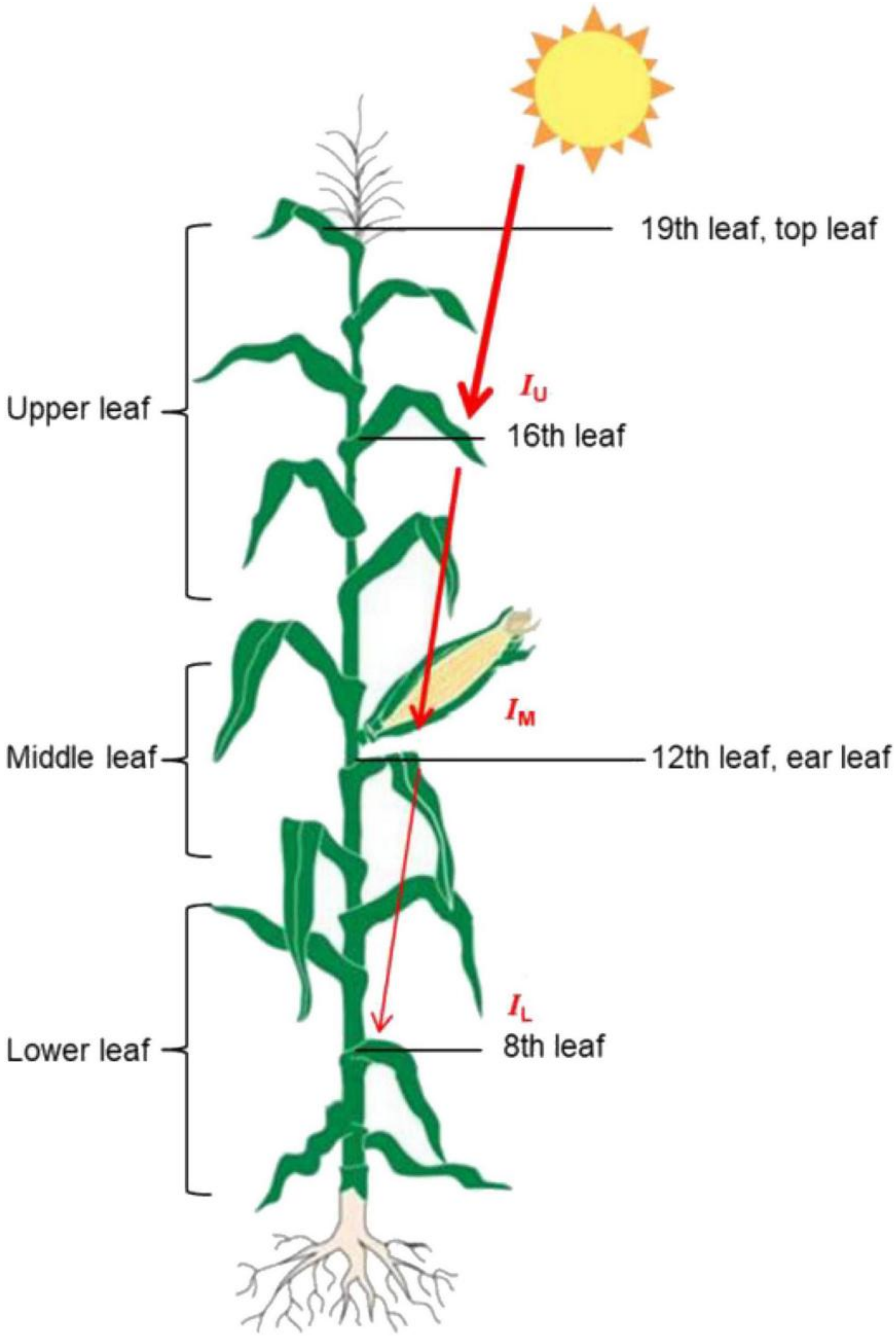

Figure 1 A schematic model depicting the leaf position and incident light of maize. The I_U, and I_O, I_M, and I_L are PAR values on a horizontal level at upper, middle and lower leaf layers. The thickness of the red arrows represent the light density that is intercepted by different leaf positions (Adopted from Tian et al., 2022)

3.2 Intra-population competition and nutrient distribution patterns

The denser the density, the more intense the competition for nutrients. This is a fundamental rule. Water, light and nutrients have all become scarce resources. The opportunities for individual plants to obtain them have decreased, and the distribution of nutrients will also become more skewed (Li et al., 2018). Especially in plots where soil supply is uneven, the root systems compete more fiercely with each other, and in the end, it may even lower the overall yield. In contrast, medium density is more stable, with a more uniform distribution of canopy nutrients and higher nitrogen utilization efficiency. However, if the density continues to increase, the space and nutrients allocated to each plant will be less, the photosynthetic nitrogen efficiency of the lower leaves will be limited, and the nutrient deficiency phenomenon will be more prominent (Wang et al., 2019; Tang, 2024).

3.3 Growth period regulation and plant uniformity under high-density conditions

High-density planting seems to grow fast and the canopy takes shape quickly, but this is not always a good thing. The leaves age too early, especially when they are too dense, compressing the entire rapid growth period (Wu et al., 2024). Not all varieties can adapt so well. Some dense-resistant materials can maintain a relatively stable canopy and photosynthetic state even in high-density environments, with small yield fluctuations (Ye et al., 2025). However, the issue of uniformity is not solely dependent on variety; it is also related to management. For instance, how nitrogen fertilizer is used and whether the variety is compact can both affect the consistency of the plants and the duration of their growth. Only by properly matching these management measures can the dense planting system perform more stably.

4 Breeding Strategies for Lodging Resistance under High-Density Conditions

4.1 Evaluation and utilization of lodging-resistant germplasm resources

Not all corn varieties can stand firm in high-density environments. Screening good germplasm resources is the first step in breeding varieties resistant to lodging. In recent years, the screening work has covered hundreds and thousands of inbred lines and hybrids. Among them, bending strength, stem thickness, pericarp hardness, spike height, and stem cellulose content have become several recurring core indicators. However, some traits do not alone indicate the issue. For instance, a high spike position does not necessarily mean that it will definitely fall over. It is necessary to consider them comprehensively. The results of clustering and principal component analysis did provide quite a few clues - for instance, among 220 inbred lines, in groups like Luda Hongsui, some key alleles were particularly prominent (Zheng et al., 2023). Improved varieties like J133A, JM25, JM115, and JM1895 have performed exceptionally well. They are not only less prone to collapse but also have decent yields, making them suitable for mechanization (Yang et al., 2024). However, it should be noted that environmental impacts cannot be ignored. Lodging resistance is not just about performing well in one plot; it is best to verify it in multiple sites over many years.

4.2 Genetic improvement of target traits and marker-assisted selection

When it comes to breeding, relying on experience to "guess" is no longer sufficient. One has to rely on molecular means to do things meticulously. Traits related to lodging resistance, such as stem thickness, stem bending resistance, and pericarp hardness, have now identified many candidate genes and loci through GWAS and QTL mapping. However, many of these superior alleles have not yet been truly introduced into mainstream varieties. That is to say, there is still much room for improvement. Techniques such as molecular marker-assisted selection (MAS) offer breeders a shortcut - they can specifically introduce fragments related to stem strength, plant type, and cell wall structure directly into the high-yield background. For instance, through transcriptome analysis, it was found that genes of those cell wall biosynthesis pathways were frequently upregulated in anti-inversion lines, which precisely supports the application of such molecular markers (Guo et al., 2021). However, relying solely on molecules is not enough. It is still necessary to combine on-site performance, taking a two-pronged approach of phenotyping and molecules, in order to improve efficiency.

4.3 Integrated breeding approaches for compact plant architecture and lodging resistance

To carry out high-density planting and ensure that the varieties can withstand the "crowding", efforts must be made simultaneously in terms of plant shape and resistance to lodging. The current approach is quite different. It's not just about who grows faster or more, but rather about having a low center of gravity, a reasonable distribution of dry matter, and a strong root system. Some hybrid varieties exhibit this "compact" structure: both the plant and the spike position are relatively short, and more dry matter sinks to the base of the stem. Such a structure is conducive to stabilizing the center of gravity, improving lodging resistance, and the yield does not decrease (Zhou and Liang, 2024). In addition, through genome-wide association analysis and double haploid lines, some genomic regions that control these traits have been identified, which provides a direction for simultaneous improvement using genomic selection or MAS. One more point that cannot be ignored is that the combination that can resist lodging and achieve high yields should be selected from the heterosis group, especially those parent resources with strong compatibility, as the probability of successful breeding will be greater.

5 Case Studies: Application of High-Density Lodging-Resistant Maize Varieties in Different Ecological Regions

5.1 Northeast China: density adaptation performance of varieties such as ‘Zhengdan 958’

In Northeast China, when growing corn, the conditions of temperature and accumulated temperature are always an inescapable reality. Zhengdan 958 (ZD958) is popular in this area because it can still maintain a good yield performance under changes in heat and precipitation. However, this variety is not all-round - for instance, in high-latitude regions with low accumulated temperature, its grain weight and total yield are not so ideal. It performs best between 3450 ° C and 3,700 ° C. Even so, if the density is increased too high or the temperature does not cooperate, the grouting speed will slow down and the risk of lodging will also increase rapidly. Some experiments also pointed out that interplanting ZD958 with taller varieties not only reduces lodging but also does not result in yield loss - the reason is that ZD958, being short, instead serves as a natural support and helps optimize the light distribution of the stand (Ren et al., 2025). Of course, density must be combined with agricultural techniques, such as precise irrigation and farming adjustments, to bring out its advantages.

5.2 North China Plain: comparative performance of ‘Denghai 605’ under medium and high densities

In North China, 'Denghai 605' (DH605) seems to be better at consuming high-density substances than ZD958. Field trials have shown that its yield remains stable at a planting density of approximately 78,000 plants per hectare, and its resistance to lodging is also strong enough. If the density is further increased, the output can still rise a little bit, but the prerequisite is that management cannot be relaxed (Liu et al., 2022). The reason why it stands steadily is mainly because of its stable plant shape, hard stems and high lignin content. In contrast, some common varieties tend to wobble at this density. However, it's not the case that the denser it is, the better. Both too dense and too sparse densities will lower the light utilization efficiency (RUE) and yield. Therefore, the density setting cannot be uniform and depends on the specific plot and the year. Growth regulators like enpaclozole, when combined with scientific management, can also further stabilize its performance.

5.3 Southwestern Hilly Areas: combined effects of high-density varieties and lodging control measures

When growing corn in hilly areas, it is not only necessary to consider whether the variety is suitable, but also how the land is laid out and the density is arranged. In the high-altitude areas of southwest China, varieties like Jinyu 838 and Xingzhongyu 801 can achieve a yield of over 12.8 tons per hectare at a density of 82,500 plants per hectare (Cheng et al., 2025). This sounds quite good, but as the density increases, the problem of lodging often follows. Especially in areas with strong solar radiation, frequent rainfall and strong winds, the challenge of resisting lodging is more obvious (Figure 2) (Lei et al., 2025). To achieve stable production, it is not enough to rely solely on the resistance of the variety. The corresponding management measures must keep up, such as using some growth regulators, adjusting the farming methods or flexibly arranging the density. Selecting hybrid varieties with thick stems, deep root systems and reliable performance in the local area is the key for these regions to follow a high-density route.

6 Challenges and Optimization Strategies in Field Application

6.1 Impact of agronomic practices on lodging resistance (e.g., fertilization and planting density)

High-density corn planting is not simply a matter of "more planting means more harvest". There are many details behind it that affect the risk of lodging. For instance, the management of nitrogen fertilizers is quite meticulous.

It's not that the more you give, the better. Some studies suggest that a nitrogen fertilizer application rate of 225 kilograms per hectare is more appropriate. Combined with fractional fertilization, it can make the stems thicker, increase the lignin content, and develop the root system more solidly. Thus, it can not only stabilize the plant height and ear position but also control the lodging rate, and the yield will increase instead (Gao et al., 2024). However, if too much nitrogen fertilizer is added and the density is not properly adjusted, the plants are more likely to grow wildly, becoming tall and soft, and a single wind or rain may cause a large number of them to fall over. In contrast, deep plowing is more effective in enhancing the dry matter and mechanical strength of the stems than shallow plowing, and is more beneficial in resisting lodging. There is also the factor of line spacing. By adjusting it, the light distribution can be improved, making the base internodes more solid and thereby indirectly reducing lodging (Jin et al., 2023; Liu et al., 2023). In addition, some plant growth regulators such as envalazole and EDAH can effectively control plant height and enhance stem toughness, and are particularly useful in close planting conditions (Xu et al., 2017).

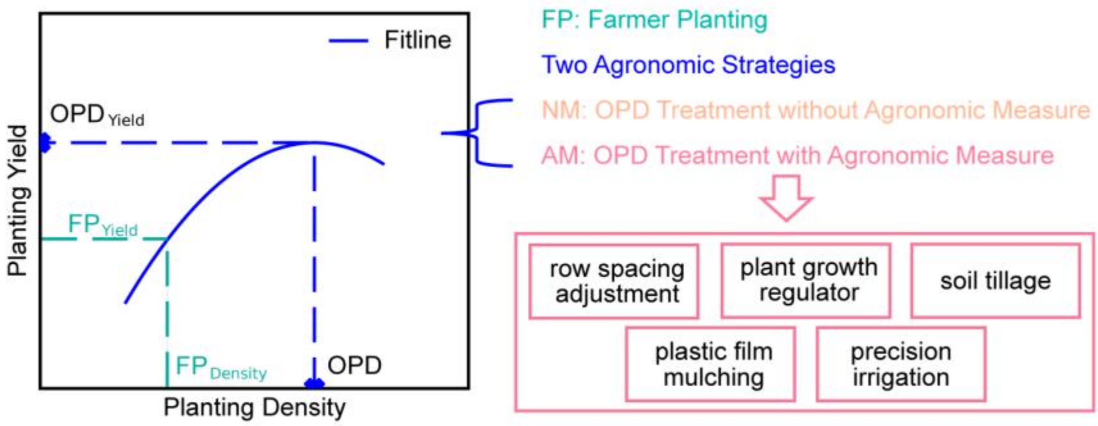

Figure 2 Definition of optimal planting density (OPD) and OPD yield for FP, NM, and AM (Adopted from Lei et al., 2025)

6.2 Lodging evaluation standards and efficient field monitoring technologies

The problem of lodging cannot be judged merely by visual inspection. How to assess and monitor it is also quite crucial. Some indicators, such as the bending resistance of the stem, the penetrating power of the fruit peel, the diameter of the internodes and the uprooting force, etc., are directly related to the lodging rate. The higher the value, the lower the risk of lodging. Nowadays, many new technologies have also been put into use, such as root extraction resistance testers, mechanical testing equipment, and even remote sensing methods, all of which can help collect these data quickly and objectively (Guo et al., 2021). Especially when breeding varieties or adjusting management strategies, this batch evaluation capability is particularly valuable, and precision agriculture thus has a more solid data support.

6.3 Adaptability of lodging-resistance technologies across diverse ecological zones

Not every anti-lodging plan works everywhere. When the climate conditions change, the strategy must also be adjusted accordingly. In areas with high altitude and strong sunlight, the internodes of plants tend to be more robust. However, in the event of frequent heavy rain or wind disasters, even the strongest stem and root structure may not be able to withstand it. Therefore, different ecological zones require corresponding and compatible variety combinations. For example, it is more reliable to select those types with high lignin content, compact structure and well-developed root systems. Of course, in addition to choosing varieties, the arrangement of density and the management of fertilizer and water also need to be adjusted in accordance with local environmental conditions. After all, a truly practical anti-lodging system depends on whether it can really run in the field (Zhang et al., 2024).

7 Conclusion and Future Perspectives

Does high-density planting necessarily mean high risk? It might have been in the past, but not necessarily now. The current hybrid varieties of corn are not like those tall but easily fallen types in the early years. The stems are thicker, the roots are more firmly planted, and the plant shape is more compact. It can still hold its ground in a dense planting environment, with no reduction in yield and a lower lodging rate. Especially in intensive planting systems, lodging has always been a major problem, often leading to reduced yields. However, if the genetic advantage of lodging resistance can be well combined with some effective agronomic measures, such as intercropping of short-stemmed varieties, adjusting row spacing, using plant growth regulators, or implementing some personalized nitrogen fertilizer management, both yield and stable yield can actually be achieved simultaneously. What's more interesting is that these strategies do not "clash" with each other; instead, they often complement each other, and the combined effect is much stronger than a single improvement.

However, when it comes to preventing lodging, external management alone is not enough; it is necessary to truly understand how it occurs at the genetic level. Future research should focus more on the fundamental aspects of plants themselves, such as the content of lignin and cellulose in the stems, the distribution pattern of the root system, and how carbohydrates are actually allocated. These seemingly "behind-the-scenes" factors often determine whether the plants can withstand the wind and rain. Meanwhile, new tools such as remote sensing technology, unmanned aerial vehicle (UAV) field inspection, and high-throughput phenotypic analysis can now screen out germplasm resources with dominant traits more quickly and accurately. As for the work in the fields, such as precise nitrogen application, deep plowing, and canopy regulation, they remain an indispensable part of enhancing the system's resistance to lodging.

Is there really only one choice between yield and lodging resistance? There is no standard answer to this balance problem at present. But precisely because of this, it is even more necessary for breeders and agronomists to work together to find solutions that can adapt to different environments and take both into account. In the next stage, when molecular markers, genomic selection, and even CRISPR and other editing tools are widely applied, it will become more realistic to stack alleles that add points to stem and root strength, compact plant type, and stress tolerance. Not to mention that smart agriculture is taking over, bringing sensors, drones and data analysis into the fields. Before a fall occurs, the system can detect it and respond in advance. By then, the integration of genetic improvement and digital technology may be a crucial step in promoting the full implementation of the anti-lodging system for densely planted corn, and it will also provide dual guarantees for food security and agricultural income.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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