RESEARCH ARTICLE

The effects of the combined application of plant growth regulators and multi-source data on maize lodging resistance and yield

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In the mountainous regions of southwest China, frequent severe convective weather events cause corn lodging, which has become a key factor limiting yield. This study investigated whether the application of plant growth regulators could simultaneously enhance corn lodging resistance and yield under the risk of severe convective weather in the southwestern mountainous region. To explore the effects of plant growth regulator (PGR) application on corn lodging resistance and yield, a three-year split-plot trial was conducted in Bijie, Guizhou, China from 2022 to 2024, utilizing multi-source data collection techniques. The main experimental area focused on application timing at the 6-leaf stage (V6), at the 8-leaf stage (V8), and pre-silking, while the sub-area tested eight PGR application schemes. The study concurrently collected plant morphology, stem mechanical properties including stem pith puncture resistance, bending strength, and center of gravity height, and multi-source unmanned aerial vehicle (UAV) remote sensing characteristics. Treatment effects were evaluated using split-plot analysis of variance and cross-year linear mixed models. A remote sensing-ground regression model and lodging grading system were established. Results showed that the yield of rapeseed treated with paclobutrazol and brassinosteroid reached 8.79 tons per hectare, representing a 12.4% increase compared to the control. Stem bark puncture resistance increased from 52.8 N to 71.2 N with lodging resistance improving by 61%. Net photosynthetic rate of flag leaves increased to 30.2 μmol/m²·s during the grain filling stage. The coefficient of determination for estimating lodged area using the normalized difference red edge index was 0.64. The overall accuracy of the four-level lodging classification reached 0.874 with a Kappa coefficient of 0.842. Cross-year integration revealed a significant main effect of the "supplemental application strategy" with a partial effect size of approximately 0.41. This study demonstrated that multi-source monitoring combined with ground calibration could provide rapid, deployable diagnostic and management support in complex mountainous environments, offering valuable application potential for maize production in high-risk areas.

Keywords: corn; plant growth regulator; lodging resistance; yield; multi-source data.

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Introduction

Corn is a vital grain and forage crop in China. In recent years, the advancement of dense planting, high-yield, and mechanized harvesting technologies has led to elevated plant centers of gravity, increased canopy shading at the upper canopy level, and combined wind and rain stress. These factors have made lodging one of the key constraints limiting stable and increased production in mountainous and hilly regions [1]. The mountainous terrain in southwest China is fragmented with pronounced slope positions and wind corridor effects. Severe convective weather events occur frequently with high spatial heterogeneity. Field-scale extreme winds and intense short-duration rainfall are more likely to induce varying degrees of lodging. These factors not only cause direct yield losses but also exacerbate ear contamination and mechanical harvesting losses [2]. Currently, plant growth regulators (PGRs) serve as crucial tools for regulating plant morphology and physiological processes. They have demonstrated potential pathways for enhancing lodging resistance across multiple crops by inhibiting excessive internode elongation, thickening stem walls, and optimizing plant stand structure [3]. Common inhibitory regulators such as chlormequat chloride (CCC) and triazole compounds paclobutrazol (PBZ) and uniconazole (S-3307) can downregulate the gibberellin synthesis pathway, shorten basal internodes, and increase stem mechanical strength. Growth-promoting compounds like brassinosteroids (BR) help maintain leaf function and enhance grain filling efficiency [4, 5].

The lodging of corn is influenced by multiple factors including variety, cultivation practices, and environmental conditions. At the cultivation level, Cui *et al*. confirmed that, while increasing planting density was an effective approach to boosting yields, it also placed higher demands on varieties' lodging resistance. In trials, the more lodging-resistant hybrid ‘Fm985’ achieved dual advantages of lower lodging rates and higher yields under high-density conditions by optimizing stem mechanical properties [6]. Guo *et al*. found that, compared to traditional plastic mulch coverage, the side-seeding technique significantly improved root architecture in the 0 - 40 cm soil layer of corn, thereby enhancing plant resistance to bending and anchoring capacity, which ultimately reduced lodging rates while increasing yield [7]. Ahmad *et al*. demonstrated that optimizing nitrogen fertilizer application rates and fractionating applications effectively improved stalk morphology and mechanical strength in high-density corn, while boosting root growth and lignin content. This approach represented a key strategy for synergistically achieving lodging resistance, stable yields, and environmental sustainability [8]. In addition to optimizing cultivation practices, applying PGRs serves as a direct method for regulating corn lodging resistance. Ren *et al*. studied the novel regulator Ethylhexanoyl Dipalmitoyl-sn-glycero-3-phosphate (EDAH) and revealed that appropriate doses of EDAH effectively reduced plant height and ear height while enhancing stem bending resistance. It could achieve both lodging resistance and stable yields under high-density planting conditions [9]. Noein *et al*. examined the effects of various PGRs under drought stress and indicated that specific formulations containing 6-benzylaminoadenine and proline significantly improved physiological processes such as nitrogen metabolism in corn, effectively mitigating the negative impact of drought on yield [10]. Zhang *et al*. discovered that non-lodging-sensitive varieties yielded higher under non-lodging conditions, revealing a negative correlation between lodging resistance and yield potential influenced by both variety and environmental factors [11]. Peng *et al*. validated that unmanned aerial vehicle (UAV) multispectral remote sensing could accurately assess key phenological stages and yield of rice [12]. Furthermore, Hassani *et al*. combined UAV multi-source data with machine learning to achieve reliable estimation of key wheat parameters such as plant height and nitrogen content [13]. Meanwhile, Herr *et al*. highlighted that UAV high-throughput phenotyping technology was improving crop breeding efficiency by quantifying complex traits, providing a reference for research methodologies [14].

Numerous researchers have investigated cultivation and chemical control measures for corn lodging resistance, as well as high-throughput phenotyping technologies for crop traits. However, current research remains largely focused on evaluating the efficacy of individual control measures. There is insufficient investigation into the synergistic mechanisms of combining different types of regulators, and the integration of high-throughput phenotyping technology with agronomic control measures has yet to be fully explored. Particularly, there is a lack of validation in complex mountainous environments and insufficient understanding of how to synergistically enhance lodging resistance and yield under high-density planting conditions. This research systematically investigated the synergistic mechanisms of combined PGRs on corn lodging resistance and yield under high-density planting in complex mountainous environments. A three-year field trial was conducted utilizing multi-source data collection methods, which integrated UAV multispectral remote sensing, stem mechanical property testing, and cell wall component analysis to construct a comprehensive lodging resistance evaluation system. The findings of this research provided a continuous evidence chain from plant geometry to mechanics and offered rapid, deployable management strategies to mitigate weather-induced agricultural risks, ultimately ensuring yield stability in vulnerable crop production areas.

Materials and methods

Overview of the pilot zone

The study area located in the Wumeng Mountains of Qixingguan District, Bijie, Guizhou, China (27°18′N, 105°17′E), the junction of Sichuan, Yunnan, and Guizhou provinces. Karst highland and hilly terrain accounted for 93% of the area with elevations ranging from 1,400 to 1,900 meters, and a maximum elevation of 2,900.6 meters. The slopes were steep, and corn lodging frequently occurred under wind and rain conditions. The region featured a subtropical monsoon climate with an average annual temperature of 13°C and annual precipitation ranging from 900 mm to 1,400 mm, concentrated between May and September. Annual sunshine hours ranged from 1,100 to 1,800 hours with a frost-free period lasting 250 to 266 days. The transition between spring and summer frequently brought intense convective weather. In April 2024, multiple occurrences of hail and strong winds provided a natural stress environment for lodging research. The soil consisted primarily of yellow soil, interspersed with limestone soil, yellow-brown soil, and purple soil, with a pH value ranging from 6.3 to 8.2. The 0 - 20 cm topsoil layer contained 30.7 g/kg of organic matter, providing stable water and nutrient retention capacity. The cropping system consisted of dryland corn-potato or buckwheat rotation. Plastic mulching increased yields by 1.2 - 1.5 t/hm². Mature varieties and cultivation techniques were employed, meeting requirements for lodging resistance regulation and monitoring research [15]. The experimental soil was tested to have a pH of 6.5 - 7.2, organic matter content of 25 - 35 g/kg, alkali-hydrolyzable nitrogen of 120 - 180 mg/kg, available phosphorus of 10 - 20 mg/kg, and readily available potassium of 110 - 180 mg/kg.

Test materials

The test crop was medium-maturity commercial hybrid maize variety “Bidan 999” (Bijie Academy of Agricultural Sciences, Bijie, Guizhou, China), which was specifically adapted to the high-altitude mountainous environments of the Wumeng Mountains, demonstrating stable performance under high-density conditions and superior lodging resistance. Seeds were tested for purity, germination rate, and moisture content before being accepted into the trial. PGRs were formulated according to the principle of “inhibiting internode elongation, enhancing stem wall strength, and balancing overall productivity”, which included PBZ, uniconazole (S-3307), and CCC served as primary inhibitory agents, while BR functioned as a growth-promoting and strengthening supplement. Prohexadione-Ca was additionally included as an alternative inhibitor for mechanism comparison. All chemicals were either analytically pure or registered agricultural formulations and purchased from Solarbio Life Sciences (Beijing, China). Solutions were prepared using deionized water and uniformly supplemented with 0.05% Tween-20 nonionic surfactant (v/v) to ensure leaf wetting and uniform deposition [16]. Basic nutrient inputs were converted based on pre-experiment soil test results and maintained uniformly across treatments using a recommended conventional N-P-K combination of N 180 - 210 kg/hm^2, P_2O_5 75 - 90 kg/hm^2, K_2O 120 - 150 kg/hm^2 to avoid fertilizer variations interfering with regulator effects. Considering the relationship between stem strength formation and silicon deposition, silicon-potassium fertilizer/metasilicate in the bottom application served as one component of the unified base fertilizer but was not treated as an independent factor.

Experimental design

The experiment was conducted over three consecutive seasons including summer planting and autumn harvest from 2022 to 2024, employing a randomized block split-plot design. The main block was the application timing with three levels of 6 - 7 leaf stage (V6), 8 - 9 leaf stage before jointing (V8), and 7 - 10 days before tasseling/boot stage (VT). The sub-plot factor was the regulator application strategy with 8 levels including water control (CK), single application of CCC, single application of PBZ, single application of S-3307, single application of BR, and three binary “inhibitor + BR” combinations of CCC + BR, PBZ + BR, S-3307 + BR. The main × sub-plot factor was fully factorial with 3 replications. The plot area measured 6 m × 8 m with 1 - 2 rows of protective rows established around the perimeter [17]. Application was performed using backpack fine-mist sprayers or multi-rotor crop protection UAVs with a spray volume of 450 – 600 L/ha^2. Droplet coverage was achieved under clear, low-wind conditions with the wind speed less than 3 m/s. Formulation rates were calibrated based on preliminary trials with 800 – 1,200 mg/L of CCC, 100 -200 mg/L of PBZ, 30 – 60 mg/L of S-3307, 0.01 – 0.05 mg/L of BR. For combined applications, each component was applied at 60 – 70% of its single-application rate to minimize risks of antagonism or excessive inhibition [18]. Basal fertilizer was applied uniformly throughout the soil layer. Nitrogen fertilizer was applied as a single topdressing before the jointing stage, accounting for 40% of the total application rate. Irrigation and pest/disease/weed management followed local green, high-quality, and efficient technical protocols. To facilitate multi-source data collection, each plot featured a 10-meter standard measurement strip at its center for assessing manual traits, mechanical properties, and sampling. Lodging ratings and canopy phenotypes at the plot level were captured through multi-temporal aerial surveys using UAV multispectral/red-green-blue (RGB) imagery from tasseling to grain filling. This data characterized regional lodging severity and temporal recovery patterns.

Test items and methods

Yield was determined based on actual harvest per plot, excluding end rows and border rows with harvest limited to the central effective rows. Yield was converted to a grain moisture content of 14%. For indoor seed evaluation, ear length, number of rows per ear, number of kernels per row, and thousand-kernel weight were measured at 20 ears per plot. Plant morphology was measured once at 10 – 12 days after silking and again at the wax ripeness stage. Stem mechanical properties were measured at the second internode above ground level with stem skin puncture resistance (SPR) using a 2 mm cone digital dynamometer to record maximum force and bending strength peak force recorded at specified span loading until breakage. The lodging resistance index was calculated as bending strength divided by center of gravity height measured post-silking. The basal internodes were collected during the wax ripening stage, dried at 65 – 70°C, pulverized, and then analyzed for lignin, cellulose, and hemicellulose using the Van Soest method [19]. Canopy lodging was obtained using UAV-derived RGB orthoimages and canopy height models (CHM), which combined with vegetation indices including the normalized difference vegetation index (NDVI) and normalized difference red edge (NDRE), as well as oblique texture features such as the tilt-texture index (TTI) and gray-level co-occurrence matrix (GLCM) contrast for grading and lodging area extraction with results verified by ground plot sampling. Flag leaf or functional leaf photosynthesis was measured during the mid-grain filling stage on sunny days between 12:00 - 13:00, recording net photosynthetic rate

(Pn), stomatal conductance (gs), transpiration rate (Tr), and intercellular CO_2 concentration (Ci) with multi-point averaging. Meteorological data were obtained from the nearest meteorological station or reanalysis grid cells at the same coordinates. Daily precipitation and temperature data during the growth period were extracted for environmental covariate analysis [20].

Data processing and statistical analysis

Following the completion of data entry and outlier removal, the raw data were analyzed using annual analysis and cross-year analysis. Within each year, a split-plot analysis of variance (ANOVA) was conducted to test the effects of the application period (main plot) and combination strategy (subplot), along with their interaction. Cross-year data were combined using a linear mixed model with year/plot group as random effects and period strategy as fixed effects. Prior to model fitting, normality and homogeneity of variance were checked. Logit or square root transformations were applied as needed for percentage or ratio-type variables. Multiple comparisons were performed using Tukey's HSD test with a significance threshold of $P < 0.05$, reporting both 95% confidence intervals and partial η^2. Key factors were selected through stepwise or ridge regression followed by estimation of direct and indirect effects using structural equation modeling (SEM) or partial least squares path modeling (PLS-PM). The relationship between UAV lodging severity or proportion and yield was analyzed using Beta regression or generalized linear models with logit links, incorporating covariates such as wind speed and precipitation to control for environmental confounding. Correlation and partial correlation analyses were conducted for mechanical and cell wall parameters. The functional relationships between rupture pressure ratio (RPR), stem diameter, wall thickness, and bending strength were compared using the akaike information criterion (AIC) and Bayesian information criterion (BIC). All statistical analyses and graphing were performed using R software (version 4.3.1) (https://www.r-project.org/). Microsoft Excel (Microsoft, Redmond, WA, USA) was used solely for data cleaning and traceability management.

Results and discussion

Influence of PGRs on corn yield and composition factors

The impact of PGRs on corn yield and composition factors demonstrated that compared to CK's yield of 7.82 t/ha, PBZ + BR achieved a converted yield of 8.79 t/ha, representing a 12.4% increase. CCC + BR and S-3307 + BR yielded 8.55 and 8.66 t/ha, respectively, both consistently higher than single-agent treatments. The yield increase was mainly attributed to the synergistic contribution of grain number per panicle and grain weight. PBZ + BR had a higher thousand-grain weight of 322.7 g and a higher number of grains per row per panicle of 34.0 × 15.7 compared to CK's 305.7 g and 32.1 × 14.6. The yield of BR applied alone (8.01 t/ha) was close to that of CK, but it improved grain weight and number of rows per panicle without significantly sacrificing panicle number. Inhibitor application alone with PBZ, S-3307, CCC demonstrating 8.42, 8.33, 8.06 t/ha, respectively, was intermediate between the two, indicating that the combined application of inhibitor + growth promoter more readily balanced both population grain filling and grain formation (Table 1). The split-plot ANOVA (Type III) results indicated that, among the main effects, the application strategy contributed the most to yield variation with F = 18.64, partial η^2 = 0.414, followed by the application period with F = 7.83, partial η^2 = 0.078. A moderate interaction existed between these two factors with F = 2.17, $P < 0.05$, indicating that selecting a specific application scheme explained yield variation more strongly than changing the application timing alone. However, the window effects across different periods still required the optimal combination to be identified within the comprehensive ranking of 3.6. The year effect was significant ($P < 0.001$), confirming the necessity of adopting a mixed-effects model for cross-year integration.

Table 1. Effects of PGRs on corn yield and yield components (cross-year marginal means, Tukey 0.05).

Treatment	Grain yield (t/ha, 14% MC)	Ears (10^4/ha)	Ear length (cm)	Kernel rows	Kernels per row	1000-kernel weight (g)	95% CI	Tukey group
CK	7.82	6.92	17.2	14.6	32.1	305.7	0.28	e
CCC	8.06	7.05	17.6	15.1	32.7	309.4	0.29	d
PBZ	8.42	7.11	18.1	15.4	33.4	316.8	0.31	bc
S-3307	8.33	7.09	18.0	15.3	33.2	314.6	0.30	cd
BR	8.01	7.03	17.7	15.0	32.8	312.1	0.27	de
CCC + BR	8.55	7.18	18.3	15.5	33.7	318.5	0.32	ab
PBZ + BR	8.79	7.24	18.6	15.7	34.0	322.7	0.33	a
S-3307 + BR	8.66	7.19	18.5	15.6	33.9	320.9	0.31	ab

Note: Different lowercase letters within the same column indicated significant differences among treatments at $P < 0.05$.

Table 2. Final growth values and plant architecture remodeling (pre-harvest fixed points, cross-year least squares means (LSMEANS)).

Treatment	Height (cm)		Ear height ratio (%)	Internode length (cm)			Basal stalk diameter (cm)	Rind thickness (mm)	LAI	SPAD
	Plant	Ear		1st	2nd	3rd				
CK	242.3	114.2	47.1	15.9	16.7	17.4	2.61	3.21	3.58	44.8
CCC	232.6	108.3	46.6	14.8	15.8	16.3	2.74	3.34	3.52	45.9
PBZ	206.8	86.1	41.6	12.7	13.4	14.1	2.89	3.61	3.47	47.3
S-3307	211.4	89.7	42.4	13.1	13.9	14.5	2.83	3.52	3.49	46.7
BR	238.7	110.1	46.1	15.2	16.1	16.8	2.68	3.28	3.86	48.5
CCC + BR	208.9	88.5	42.4	12.6	13.3	14.0	2.92	3.65	3.55	47.8
PBZ + BR	199.8	80.9	40.5	12.2	12.9	13.5	2.96	3.71	3.64	49.1
S-3307 + BR	204.6	84.2	41.2	12.5	13.2	13.8	2.91	3.63	3.60	48.7

Effects of PGRs on corn growth, development, and morphology

Final growth values and plant architecture remodeling showed that the growth-regulating treatment significantly corrected plant architecture and lowered the center of gravity. The plant height under PBZ + BR was only 199.8 cm with an ear-to-stem ratio of 40.5%, compared to 242.3 cm and 47.1% under CK. The basal stalk diameter increased from 2.61 cm to 2.96 cm, and the stalk bark thickness increased from 3.21 mm to 3.71 mm. BR alone showed more pronounced improvements in leaf area index (LAI) and soil plant analysis development (SPAD) with 3.86 and 48.5, respectively, but its correction of internode length and ear position was less effective than PBZ/S-3307 (Table 2).

Effects of PGRs on photosynthetic parameters of corn flag leaves

The flag leaf gas exchange parameters demonstrated that PBZ + BR was overall optimal across all four indicators with Pn as 30.2 μmol $CO_2/m^2 \cdot s$, representing a 12.3% increase over CK. Concurrently, gs and Tr were 0.28 mol $H_2O/m^2 \cdot s$ and 3.83 mmol $H_2O/m^2 \cdot s$, respectively, slightly elevated while Ci was 259.1 μmol/mol decreased, indicating improved coordination between photosynthetic energy supply and stomatal regulation. The values of Pn for S-3307 + BR and BR alone showed approximately 29.7 and 29.6, respectively. Inhibitor applications alone demonstrated that PBZ was 28.7, while S-3307 was 28.1, showing varying degrees of improvement over CK, with CCC exhibiting the smallest improvement (Table 3).

Effects of PGRs on the resistance to lodging in corn stalks

Stem mechanics and lodging resistance index demonstrated that PBZ + BR exhibited an RPR of 71.2 N and bending strength of 236.4 N, representing increases of 35% and 34%, respectively, compared to CK's 52.8 N and 176.4

Table 3. Flag leaf gas exchange parameters (mid-grouting period 12:00-13:00, cross-annual LSMEANS).

Treatment	Pn (μmol CO2/m²·s)	gs (mol H_2O/m²·s)	Tr (mmol H_2O/m²·s)	Ci (μmol/mol)	95% CI	Tukey group
CK	26.9	0.23	3.42	274.3	1.21	d
CCC	27.4	0.24	3.51	270.6	1.18	cd
PBZ	28.7	0.26	3.63	263.8	1.15	bc
S-3307	28.1	0.25	3.59	266.5	1.17	bc
BR	29.6	0.27	3.74	261.4	1.12	ab
CCC + BR	29.0	0.26	3.68	262.9	1.14	ab
PBZ + BR	30.2	0.28	3.83	259.1	1.10	a
S-3307 + BR	29.7	0.27	3.77	260.8	1.11	ab

Note: Different lowercase letters within the same column indicated significant differences among treatments at $P < 0.05$.

Table 4. Stem mechanics and lodging resistance index (multi-year LSMEANS).

Treatment	RPR (N)	Bending/breaking force (N)	Center of mass height (m)	Lodging resistance index (N/m)	95% CI	Tukey group
CK	52.8	176.4	1.03	171.3	4.8	e
CCC	58.9	189.3	0.98	193.2	5.2	d
PBZ	66.1	214.8	0.89	241.3	5.9	bc
S-3307	63.4	208.6	0.92	226.7	5.7	cd
BR	56.7	184.5	1.01	182.7	5.1	de
CCC + BR	68.3	222.1	0.90	246.8	6.1	ab
PBZ + BR	71.2	236.4	0.86	274.9	6.5	a
S-3307 + BR	69.5	229.7	0.88	261.0	6.2	ab

Note: Different lowercase letters within the same column indicated significant differences among treatments at $P < 0.05$.

N. Concurrently, the center of gravity height decreased from 1.03 m to 0.86 m, resulting in a lodging resistance index of 274.9 N/m, a 61% improvement over CK. The indices for CCC + BR and S-3307 + BR were 246.8 and 261.0 N/m, respectively, both representing high levels. While BR alone maintained plant population, its mechanical improvement was limited with index of 182.7 N/m (Table 4). Correlation analysis revealed that basal stalk diameter and rind thickness were strongly and positively correlated with RPR and bending force with the r values of 0.73 and 0.69 for basal stalk diameter ($P < 0.001$) and 0.66 and 0.62 for rind thickness ($P < 0.01$), respectively. Multiple regression analysis further confirmed these as the primary positive predictors for mechanical enhancement with standardized β values of 0.46 ± 0.10 for diameter and 0.31 ± 0.09 for rind thickness. Conversely, internode lengths and hollowness exhibited significant negative effects on mechanical strength with r ranges of -0.51 to -0.62 for internode lengths ($P < 0.05$) and -0.45 to -0.49 for hollowness ($P < 0.05$). The variance inflation factors (VIF) for all predictors were below 3.3, indicating negligible multicollinearity and ensuring the stability of the regression model.

Correlation analysis between UAV remote sensing parameters and ground lodging resistance indicators

Cross-validation (10-fold) regression analysis demonstrated the predictive capacity of multi-source UAV features for ground-based indicators. For continuous variable estimation, NDRE showed better performance than NDVI, achieving an R^2 of 0.64 and a root mean square error (RMSE) of 6.44% for the lodged area estimation, and an R^2 of 0.47, RMSE of 7.63 N for SPR. The CHM exhibited strong explanatory

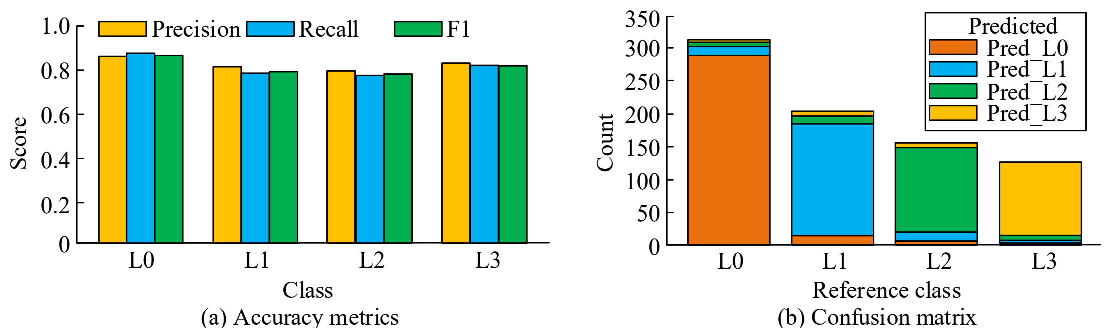

Figure 1. Performance and error distribution of multi-source fusion-based corn lodging classification.

Table 5. Comprehensive ranking of lodging resistance and yield benefits.

Treatment	Std. yield	Std. lodged area (inverted)	Std. RPR	Std. Ear height ratio (inverted)	Std. 1000-kernel weight	Overall rank	Stable under ±10% weight perturbation
CK	0.000	0.000	0.000	0.000	0.000	8	No
CCC	0.247	0.292	0.332	0.086	0.218	6	No
PBZ	0.619	0.725	0.723	0.828	0.653	4	Yes
S-3307	0.526	0.633	0.576	0.708	0.524	5	Yes
BR	0.196	0.150	0.212	0.152	0.376	7	No
CCC + BR	0.753	0.792	0.842	0.718	0.753	3	Yes
PBZ + BR	1.000	1.000	1.000	1.000	1.000	1	Yes
S-3307 + BR	0.866	0.933	0.908	0.900	0.894	2	Yes

power for bending force with an R^2 of 0.56. Furthermore, the tilt-texture index (TTI) yielded the optimal estimation for the comprehensive lodging resistance index with R^2 of 0.62 and RMSE of 25.9. Overall prediction errors remained within acceptable ranges, validating that the integrated features met the precision requirements for field-scale lodging grading and early warning systems. The performance and error distribution of the multi-source fusion corn lodging classification showed the accuracy metrics for four lodging severity levels (L0–L3), which demonstrated that the method performed most stably at the two extremes, achieving an F1 score of 0.92 for L0 and 0.87 for L3. The F1 scores for mild and moderate lodging were 0.84 and 0.83, respectively. The difference between precision and recall did not exceed 0.03 for any level (Figure 1a). The stacked confusion matrix was categorized by reference level. Among L0 cases, 290/312 were correctly classified as L0. Among L3 cases, 111/128 were correctly classified as L3 with a high proportion on the main diagonal. The primary errors were concentrated in the misclassification between adjacent grades L1 and L2 with 14 cases of L1→L2 and 14 cases of L2→L1, consistent with the challenges encountered in actual field interpretations (Figure 1b).

Comprehensive evaluation of treatments for lodging resistance and yield benefits

The comprehensive ranking of lodging resistance and yield benefits showed that PBZ + BR achieved a normalized value of 1.000 across all five indicators, ranking first overall, while S-3307 + BR and CCC + BR ranked second and third, respectively, maintaining stability under the weight perturbations. PBZ and S-3307 applied individually were ranked 4th and 5th, respectively, demonstrating significantly enhanced mechanical properties but slightly inferior group source strength compared to combined application. CCC and BR were ranked 6th and 7th due to weaker performance in several indicators with CK ranking the last (Table 5). This study demonstrated that the combined application of plant growth inhibitors and BR provided a superior pathway for synergistically enhancing corn lodging resistance and grain yield in complex mountainous environments. The results confirmed that the application strategy served as a more decisive factor in optimizing crop performance than the application timing alone. While current findings were derived from a specific ecological region in Guizhou, China, they established a robust methodological framework for integrating multi-source monitoring with agronomic control. Future research involving multi-regional validation and diverse planting densities will be essential to further refine the precision of the integrated aerial-ground early warning models and management decision systems.

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