

Table S1. Meteorological information of the cotton growth period in the experimental site.

Meteorological data	Year	April	May	June	July	August	September
Precipitation (mm)	2024	4.20	5.10	13.30	125.10	79.80	61.60
	2025	1.90	41.30	83.20	114.80	27.70	108.30
Sunshine duration (h)	2024	240.54	309.28	260.06	176.6	261.33	170.22
	2025	274.94	292.84	234.15	286.92	236.65	149.55
Maximum air temperature (°C)	2024	22.90	28.54	34.92	31.87	33.36	28.48
	2025	25.03	27.90	33.89	34.63	32.99	26.72
Minimum air temperature (°C)	2024	11.32	15.42	21.07	23.26	23.23	17.93
	2025	9.54	14.35	20.96	25.04	23.74	16.48

Table S2. Descriptive statistics (mean \pm SD) of above-ground biomass, radiation use efficiency, yield and yield components for all treatment combinations in 2024.

Experiment	Treatment	AGB	RUE	SY	LP	BW	BN
		(kg \cdot ha ⁻¹)	(g MJ ⁻¹)	(kg \cdot ha ⁻¹)	(%)	(g)	(bolls \cdot m ⁻²)
Sowing date	S1	14270.34 \pm 847.97	3.36 \pm 0.20	2496.94 \pm 96.55	52.77 \pm 2.57	4.73 \pm 0.13	34.59 \pm 0.28
	S2	12159.84 \pm 355.93	2.60 \pm 0.08	2614.68 \pm 285.83	55.05 \pm 4.37	4.74 \pm 0.15	35.84 \pm 0.82
	S3	12670.64 \pm 2389.69	2.68 \pm 0.51	2303.82 \pm 200.09	48.26 \pm 3.08	4.77 \pm 0.11	34.43 \pm 0.94
	S4	12876.84 \pm 1248.41	3.08 \pm 0.30	2209.55 \pm 191.88	45.52 \pm 3.71	4.85 \pm 0.10	34.06 \pm 0.54
	S5	12351.27 \pm 1404.90	2.62 \pm 0.30	1848.57 \pm 352.39	37.87 \pm 5.92	4.87 \pm 0.17	33.96 \pm 0.60
	S6	9195.50 \pm 1136.64	2.13 \pm 0.26	1558.55 \pm 461.28	31.43 \pm 8.68	4.95 \pm 0.18	33.00 \pm 0.82
Density	D1	6149.20 \pm 1024.91	1.74 \pm 0.29	2237.88 \pm 361.21	38.50 \pm 5.39	5.80 \pm 0.13	31.16 \pm 1.52
	D2	7428.10 \pm 2896.27	1.73 \pm 0.68	2690.99 \pm 158.21	46.97 \pm 2.76	5.73 \pm 0.22	29.99 \pm 1.04
	D3	10209.79 \pm 2466.29	2.04 \pm 0.49	2795.64 \pm 187.91	50.68 \pm 3.20	5.52 \pm 0.05	29.21 \pm 0.45
	D4	11720.12 \pm 444.33	2.41 \pm 0.09	2685.23 \pm 238.39	48.08 \pm 4.23	5.58 \pm 0.06	30.91 \pm 0.74
	D5	17945.43 \pm 3243.38	3.92 \pm 0.96	2897.60 \pm 405.09	51.76 \pm 6.88	5.60 \pm 0.13	29.52 \pm 0.65
	D6	14949.89 \pm 5206.13	3.39 \pm 1.60	2774.82 \pm 396.31	50.58 \pm 6.60	5.48 \pm 0.07	29.39 \pm 0.44
Cultivar	V1	12032.40 \pm 2463.94	2.75 \pm 0.56	2350.90 \pm 318.59	46.34 \pm 5.02	5.07 \pm 0.21	37.48 \pm 0.46
	V2	10843.19 \pm 1175.96	2.82 \pm 0.31	2082.36 \pm 385.25	44.14 \pm 8.23	4.72 \pm 0.01	35.72 \pm 0.48
	V3	12423.32 \pm 1076.37	2.85 \pm 0.25	2563.66 \pm 205.22	46.64 \pm 5.27	5.51 \pm 0.18	29.73 \pm 0.91
	V4	11916.35 \pm 3737.35	4.00 \pm 1.25	1719.75 \pm 195.61	33.84 \pm 3.56	5.08 \pm 0.15	30.68 \pm 0.43
	V5	9930.72 \pm 421.55	2.68 \pm 0.11	2846.31 \pm 149.00	63.24 \pm 2.40	4.50 \pm 0.06	35.66 \pm 0.24
	V6	12449.50 \pm 3440.02	2.76 \pm 0.76	2133.30 \pm 166.78	41.86 \pm 1.52	5.09 \pm 0.22	31.84 \pm 0.77
	V7	12486.59 \pm 937.02	2.81 \pm 0.21	3263.85 \pm 279.80	57.05 \pm 5.00	5.72 \pm 0.03	36.33 \pm 0.21
	V8	14117.89 \pm 4970.41	3.37 \pm 1.19	2394.56 \pm 124.92	55.44 \pm 3.84	4.32 \pm 0.16	37.36 \pm 1.37
	V9	13483.07 \pm 5281.41	3.35 \pm 1.31	2095.00 \pm 258.56	39.85 \pm 4.19	5.25 \pm 0.12	29.39 \pm 0.30
	V10	12304.93 \pm 4822.60	2.77 \pm 1.08	2528.59 \pm 379.28	42.38 \pm 6.02	5.96 \pm 0.08	37.69 \pm 0.35

Note: AGB, above-ground biomass; RUE, radiation use efficiency; SY, seed cotton yield; LP, lint percentage; BW, boll weight; BN, boll number per unit area. Data represent the average of three replicates for the 2024 growing season.

Table S3. Descriptive statistics (mean \pm SD) of above-ground biomass, radiation use efficiency, yield and yield components for all treatment combinations in 2025.

Experiment	Treatment	AGB (kg \cdot ha ⁻¹)	RUE (g MJ ⁻¹)	SY (kg \cdot ha ⁻¹)	LP (%)	BW (g)	BN (bolls \cdot m ⁻²)
Sowing date	S1	13420.07 \pm 1323.02	4.38 \pm 0.39	3565.02 \pm 486.33	66.37 \pm 6.43	5.36 \pm 0.35	34.78 \pm 1.70
	S2	12160.50 \pm 1574.35	3.57 \pm 1.00	3413.12 \pm 298.09	66.33 \pm 3.48	5.14 \pm 0.18	35.92 \pm 0.90
	S3	12869.39 \pm 3079.65	4.06 \pm 0.97	3312.53 \pm 510.16	61.24 \pm 9.27	5.41 \pm 0.05	35.30 \pm 0.40
	S4	13231.10 \pm 1412.57	4.67 \pm 0.50	3161.52 \pm 240.93	56.61 \pm 3.57	5.59 \pm 0.25	35.18 \pm 0.83
	S5	11027.50 \pm 2120.38	3.59 \pm 0.69	3099.49 \pm 295.17	54.96 \pm 4.03	5.63 \pm 0.13	35.07 \pm 0.31
	S6	10325.65 \pm 3305.40	4.08 \pm 1.31	3144.12 \pm 202.47	57.77 \pm 2.87	5.44 \pm 0.18	36.30 \pm 0.56
Density	D1	6721.05 \pm 811.09	2.31 \pm 0.28	3174.80 \pm 263.44	55.05 \pm 5.69	5.77 \pm 0.11	32.45 \pm 0.57
	D2	7955.62 \pm 422.01	2.59 \pm 0.14	3709.57 \pm 361.39	67.79 \pm 7.11	5.48 \pm 0.10	31.83 \pm 0.34
	D3	9567.51 \pm 546.03	2.94 \pm 0.17	3791.26 \pm 355.28	71.27 \pm 8.70	5.33 \pm 0.18	32.24 \pm 0.28
	D4	11703.11 \pm 3095.64	3.40 \pm 0.90	3749.72 \pm 122.27	71.16 \pm 3.72	5.27 \pm 0.12	32.28 \pm 0.85
	D5	11416.49 \pm 2924.95	3.11 \pm 0.80	3674.06 \pm 270.53	68.62 \pm 4.56	5.35 \pm 0.04	32.19 \pm 0.93
	D6	12335.88 \pm 5527.54	4.01 \pm 1.80	3568.17 \pm 160.81	67.19 \pm 4.52	5.32 \pm 0.14	32.80 \pm 0.23
Cultivar	V1	15398.42 \pm 1086.64	5.23 \pm 0.80	3704.40 \pm 572.89	68.27 \pm 8.42	5.41 \pm 0.21	40.59 \pm 0.45
	V2	11037.07 \pm 1307.64	3.64 \pm 0.43	3668.12 \pm 746.92	71.49 \pm 11.10	5.11 \pm 0.26	38.84 \pm 0.42
	V3	11368.11 \pm 3014.52	3.39 \pm 0.90	3528.59 \pm 709.89	66.23 \pm 11.59	5.31 \pm 0.14	31.46 \pm 1.01
	V4	12743.13 \pm 2044.79	3.57 \pm 0.57	3234.40 \pm 523.71	64.63 \pm 10.69	5.01 \pm 0.07	32.80 \pm 0.55
	V5	10790.66 \pm 1708.07	3.54 \pm 0.56	3516.20 \pm 483.79	69.90 \pm 7.40	5.02 \pm 0.28	36.85 \pm 0.87
	V6	12767.80 \pm 2534.62	3.60 \pm 0.72	4137.65 \pm 357.21	75.53 \pm 4.08	5.47 \pm 0.19	32.94 \pm 0.65
	V7	11201.84 \pm 2143.83	3.12 \pm 0.60	3655.53 \pm 484.40	71.66 \pm 8.34	5.09 \pm 0.09	37.24 \pm 0.47
	V8	14824.09 \pm 2030.25	6.39 \pm 0.70	3232.45 \pm 584.52	64.25 \pm 8.68	5.01 \pm 0.34	37.18 \pm 2.13
	V9	11519.08 \pm 2832.68	4.22 \pm 1.04	3928.19 \pm 148.05	73.24 \pm 2.63	5.36 \pm 0.10	32.42 \pm 1.03
	V10	11932.17 \pm 2198.20	3.51 \pm 0.65	3887.02 \pm 474.90	67.18 \pm 3.54	5.77 \pm 0.40	39.73 \pm 0.54

Note: Abbreviations are as defined in Table S1. Data represent the average of three replicates for the 2025 growing season.

Table S4. Pooled descriptive statistics (mean \pm SD) of above-ground biomass, radiation use efficiency, and yield components across 2024 and 2025.

Experiment	Treatment	AGB (kg • ha ⁻¹)	RUE (g MJ ⁻¹)	SY (kg • ha ⁻¹)	LP (%)	BW (g)	BN (bolls • m ⁻²)
Sowing date	S1	13845.21 \pm 1097.57	3.87 \pm 0.62	3030.98 \pm 663.76	59.57 \pm 8.64	5.05 \pm 0.42	34.68 \pm 1.10
	S2	12160.17 \pm 1020.84	3.09 \pm 0.82	3013.90 \pm 509.39	60.69 \pm 7.12	4.94 \pm 0.26	35.88 \pm 0.77
	S3	12770.02 \pm 2467.75	3.37 \pm 1.03	2808.17 \pm 652.21	54.75 \pm 9.42	5.09 \pm 0.36	34.86 \pm 0.80
	S4	13053.97 \pm 1207.98	3.88 \pm 0.95	2685.54 \pm 556.62	51.06 \pm 6.89	5.22 \pm 0.44	34.62 \pm 0.88
	S5	11689.38 \pm 1764.54	3.10 \pm 0.71	2474.03 \pm 744.29	46.41 \pm 10.40	5.25 \pm 0.44	34.51 \pm 0.74
	S6	9760.57 \pm 2295.69	3.10 \pm 1.36	2351.34 \pm 925.05	44.60 \pm 15.54	5.19 \pm 0.32	34.65 \pm 1.91
Density	D1	6435.12 \pm 883.99	2.02 \pm 0.40	2706.34 \pm 585.91	46.78 \pm 10.33	5.79 \pm 0.11	31.81 \pm 1.25
	D2	7691.86 \pm 1873.52	2.16 \pm 0.64	3200.28 \pm 611.15	57.38 \pm 12.38	5.60 \pm 0.21	30.91 \pm 1.22
	D3	9888.65 \pm 1635.86	2.49 \pm 0.59	3293.45 \pm 601.66	60.98 \pm 12.71	5.42 \pm 0.16	30.72 \pm 1.69
	D4	11711.61 \pm 1977.94	2.91 \pm 0.79	3217.47 \pm 607.17	59.62 \pm 13.14	5.43 \pm 0.19	31.60 \pm 1.04
	D5	14680.96 \pm 4518.63	3.52 \pm 0.90	3285.83 \pm 525.15	60.19 \pm 10.61	5.47 \pm 0.16	30.85 \pm 1.63
	D6	13642.89 \pm 5011.28	3.70 \pm 1.56	3171.50 \pm 511.85	58.88 \pm 10.41	5.40 \pm 0.13	31.10 \pm 1.89
Cultivar	V1	13715.41 \pm 2509.93	3.99 \pm 1.49	3027.65 \pm 849.39	57.30 \pm 13.52	5.24 \pm 0.27	39.03 \pm 1.75
	V2	10940.13 \pm 1117.32	3.23 \pm 0.56	2875.24 \pm 1018.29	57.81 \pm 17.34	4.91 \pm 0.27	37.28 \pm 1.76
	V3	11895.72 \pm 2105.33	3.12 \pm 0.66	3046.12 \pm 705.51	56.44 \pm 13.41	5.41 \pm 0.18	30.60 \pm 1.28
	V4	12329.74 \pm 2732.15	3.79 \pm 0.90	2477.08 \pm 901.81	49.24 \pm 18.31	5.04 \pm 0.11	31.74 \pm 1.24
	V5	10360.69 \pm 1208.28	3.11 \pm 0.59	3181.25 \pm 486.96	66.57 \pm 6.12	4.76 \pm 0.34	36.25 \pm 0.86
	V6	12608.65 \pm 2708.06	3.18 \pm 0.81	3135.47 \pm 1125.79	58.69 \pm 18.65	5.28 \pm 0.28	32.39 \pm 0.88
	V7	11844.21 \pm 1638.53	2.96 \pm 0.43	3459.69 \pm 413.76	64.35 \pm 10.09	5.41 \pm 0.35	36.79 \pm 0.59
	V8	14470.99 \pm 3417.66	4.88 \pm 1.87	2813.50 \pm 594.58	59.84 \pm 7.70	4.67 \pm 0.45	37.27 \pm 1.61
	V9	12501.08 \pm 3940.07	3.79 \pm 1.16	3011.59 \pm 1021.61	56.54 \pm 18.55	5.31 \pm 0.12	30.91 \pm 1.79
	V10	12118.55 \pm 3358.20	3.14 \pm 0.90	3207.81 \pm 837.47	54.78 \pm 14.28	5.87 \pm 0.28	38.71 \pm 1.19

Note: Abbreviations are as defined in Table S1. Data represent the pooled means and standard deviations across the two growing seasons.

Table S5. Coefficients of determination (R^2) of the regression models between cotton canopy structural traits and iPAR under different treatments (2024 – 2025).

Experiment	Treatment	TLN (per plant)	PH (cm)	LAI —
Sowing date	S1	0.63**	0.84**	0.63**
	S2	0.68**	0.89**	0.55**
	S3	0.61**	0.84**	0.57**
	S4	0.68**	0.84	0.64**
	S5	0.49**	0.77**	0.53**
	S6	0.64**	0.77**	0.58**
Density	D1	0.38**	0.53**	0.30**
	D2	0.59**	0.72**	0.61**
	D3	0.73**	0.83**	0.66**
	D4	0.75**	0.88**	0.67**
	D5	0.76**	0.83**	0.68**
	D6	0.48**	0.69**	0.38**
Cultivar	V1	0.76**	0.82**	0.66**
	V2	0.63**	0.80**	0.58**
	V3	0.53**	0.70**	0.51**
	V4	0.84**	0.83**	0.76**
	V5	0.73**	0.86**	0.79**
	V6	0.88**	0.80**	0.89**
	V7	0.71**	0.76**	0.74**
	V8	0.76**	0.78**	0.73**
	V9	0.85**	0.70**	0.69**
	V10	0.85**	0.87**	0.85**

Note: Data represent the R^2 values for each individual treatment. All regression models are statistically significant at $P < 0.01$.

Table S6. Variance inflation factor (VIF) diagnostics and random forest model performance metrics at the comprehensive dataset ($n=132$) and cultivar subset ($n=60$) scales.

Analysis Type	Variable	Comprehensive dataset	Cultivar subset
VIF Diagnostics	V_{cmax}	—	38.55
	J_{max}	—	26.81
	P_n	—	2.35
	G_s	—	12.52
	T_r	—	16.73
	PH	12.3	40.85
	TLN	5.12	15.61
	iPAR	6.14	8.38
	LAI	2.11	4.44
	SLN	8.98	17.94
	SPAD	1.11	1.92
	LMA	3.23	3.09
	C/N	6.98	11.90
Model Performance	Train R^2	0.88	0.86
	Train RMSE	1.24	0.55
	CV R^2	-0.01	-2.41
	CV RMSE	1.24	1.44

Note: "—" indicates that the leaf gas exchange and photosynthetic parameters were not evaluated in the comprehensive dataset. Abbreviations are listed in the Abbreviations section. CV stands for cross-validation.

Table S7. Measurement model reliability and validity assessment for the PLS-SEM.

Model Scale	Latent Construct	Indicators	Outer Loadings	Cronbach's α	Composite Reliability CR)	AVE
Comprehensive Dataset (<i>n</i> = 132)	Canopy	PH, TLN, LAI, iPAR	0.975, 0.869, 0.655, 0.884	0.87	0.914	0.729
	Leaf	SPAD, SLN, LMA, C/N	-0.414, 0.835, 0.074, -0.902	N/A	N/A	N/A
	Composition	LP, BW, BN	0.522, 0.175, 0.949	N/A	N/A	N/A
Cultivar Subset (<i>n</i> = 60)	Canopy	PH, TLN, LAI, iPAR	0.977, 0.960, 0.861, 0.949	0.954	0.867	0.88
	Leaf	SPAD, SLN, LMA, C/N	-0.414, 0.958, 0.294, -0.939	N/A	N/A	N/A
	Gas	P _n , T _r , G _s	0.538, 0.962, 0.967	0.805	0.888	0.717
	Physiology	V _{cmax} , J _{max}	0.978, 0.978	0.954	0.978	0.956
	Composition	LP, BW, BN	0.632, 0.228, 0.918	N/A	N/A	N/A

Note: N/A = Not applicable. .Single-indicator constructs are not listed as their metrics are fixed at 1.0. For the 'Leaf Functional Traits' and 'Yield Components' constructs, conventional internal consistency metrics (Cronbach's α , CR, AVE) are mathematically inapplicable. These operate as formative indices containing inherent biological trade-offs, such as the negative correlation between specific leaf nitrogen and C/N ratio, as well as the classic compensatory relationship between boll number and boll weight.

Table S8. Structural model path coefficients, bootstrapped confidence intervals, and collinearity diagnostics for the comprehensive dataset ($n = 132$).

Path Relationships	Path Coefficient (β)	p-value	95% CI Lower	95% CI High	Inner VIF
Treatment → Canopy	0.050	0.529	-0.079	0.248	1.010
Treatment → Leaf	-0.448	0.295	-0.586	0.539	1.015
Treatment → Composition	0.276	0.002	0.023	0.378	1.395
Climate → Canopy	-0.729	0.006	-0.914	-0.570	1.010
Climate → Leaf	0.111	0.688	-0.547	0.486	2.171
Climate → Composition	0.524	0.028	0.288	0.926	2.268
Canopy → Leaf	-0.353	0.264	-0.530	0.470	2.182
Canopy → Efficiency	-0.225	0.192	-0.484	0.211	2.406
Canopy → Biomass	0.537	0.000	0.397	0.666	2.464
Leaf → Efficiency	-0.094	0.499	-0.331	0.218	1.799
Leaf → Biomass	0.112	0.274	-0.158	0.180	1.809
Efficiency → Biomass	0.972	0.000	0.880	1.062	1.150
Efficiency → Composition	-0.119	0.541	-0.495	0.290	8.251
Biomass → Composition	0.172	0.367	-0.225	0.530	7.523
Biomass → Yield	-0.118	0.321	-0.355	0.109	7.605
Composition → Yield	0.918	0.000	0.718	1.003	2.791

Note: CI = confidence interval; VIF = variance inflation factor. Path coefficients (β) and 95% confidence intervals were estimated based on 2,000 bootstrap resamples.

Table S9. Structural model path coefficients, bootstrapped confidence intervals, and collinearity diagnostics for the cultivar subset ($n = 60$).

Path Relationship	Path Coefficient (β)	p-value	95% CI Lower	95% CI High	Inner VIF
Treatment → Canopy	0.170	0.000	0.080	0.253	1.000
Treatment → Leaf	0.009	0.892	-0.143	0.130	1.271
Climate → Canopy	-0.930	0.000	-0.982	-0.883	1.000
Climate → Leaf	0.948	0.176	-1.131	1.240	9.102
Canopy → Leaf	0.041	0.834	-0.360	0.401	9.374
Canopy → Gas	0.141	0.503	-0.328	0.478	3.368
Canopy → Physiology	-0.513	0.000	-0.655	-0.374	3.404
Canopy → Biomass	0.347	0.039	0.103	0.761	7.022
Leaf → Gas	0.786	0.184	-0.936	1.039	3.368
Leaf → Physiology	0.317	0.178	-0.393	0.458	4.495
Gas → Physiology	0.240	0.000	0.166	0.329	1.825
Gas → Efficiency	-0.077	0.656	-0.471	0.198	2.584
Physiology → Efficiency	0.157	0.793	-0.942	1.287	13.131
Physiology → Composition	0.566	0.027	0.029	1.048	13.349
Efficiency → Biomass	0.998	0.000	0.810	1.083	1.197
Efficiency → Composition	-0.322	0.117	-0.723	0.092	7.225
Biomass → Composition	0.201	0.325	-0.202	0.604	6.052
Biomass → Yield	-0.056	0.678	-0.346	0.210	4.270
Composition → Yield	0.901	0.000	0.808	0.977	1.214

Note: CI = confidence interval; VIF = variance inflation factor. Path coefficients (β) and 95% confidence intervals were estimated based on 2,000 bootstrap resamples.

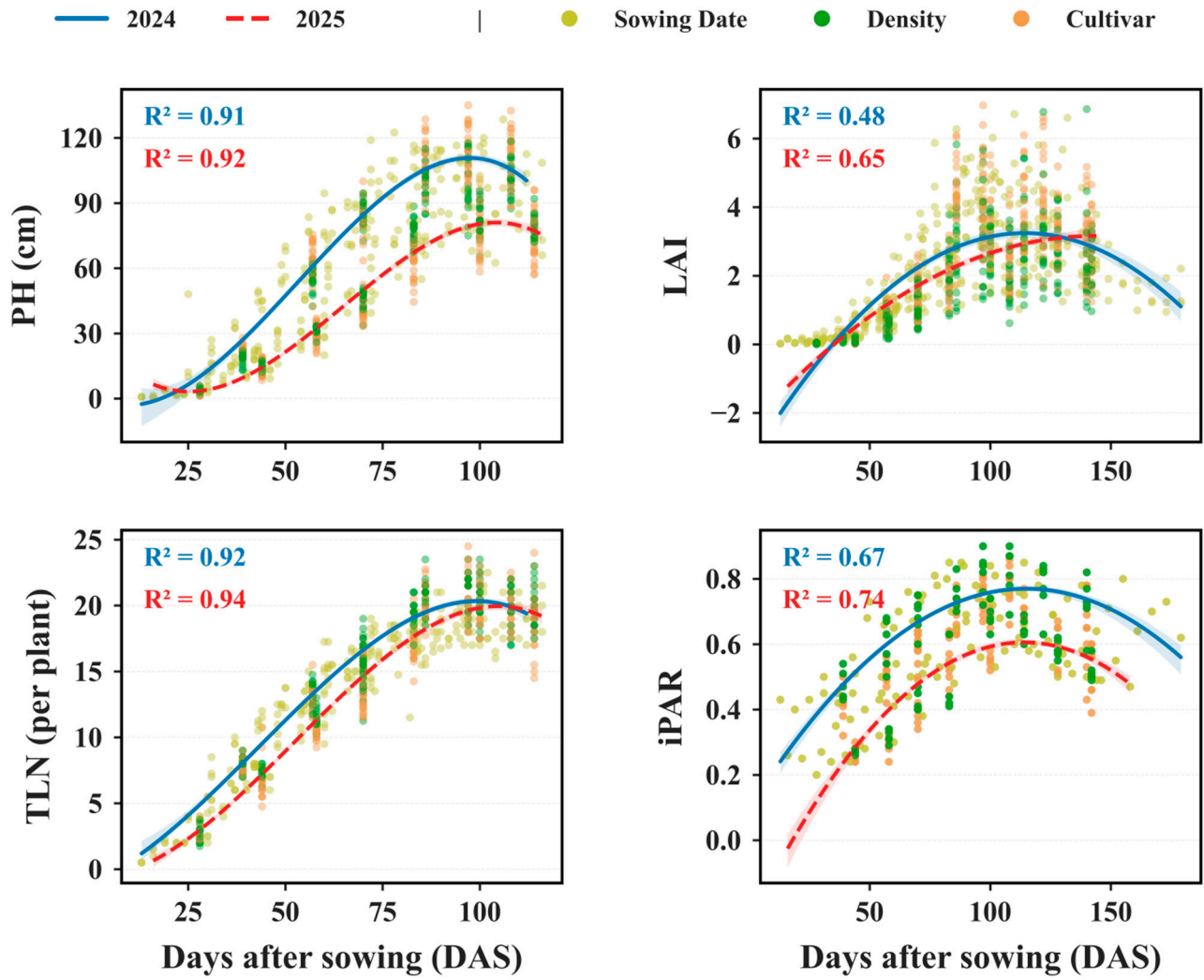


Figure S1. Temporal dynamics of cotton canopy structural traits, including plant height (PH), true leaf number (TLN), and leaf area index (LAI), and light interception rate (iPAR) throughout the growing season. Scatter points represent individual measurements at different days after sowing (DAS). The curves indicate temporal trends fitted with Logistic (for PH and TLN) or quadratic polynomial (for LAI and iPAR) models for the 2024 (solid lines) and 2025 (dashed lines) growing seasons. R^2 values indicate the goodness of fit for the respective years.

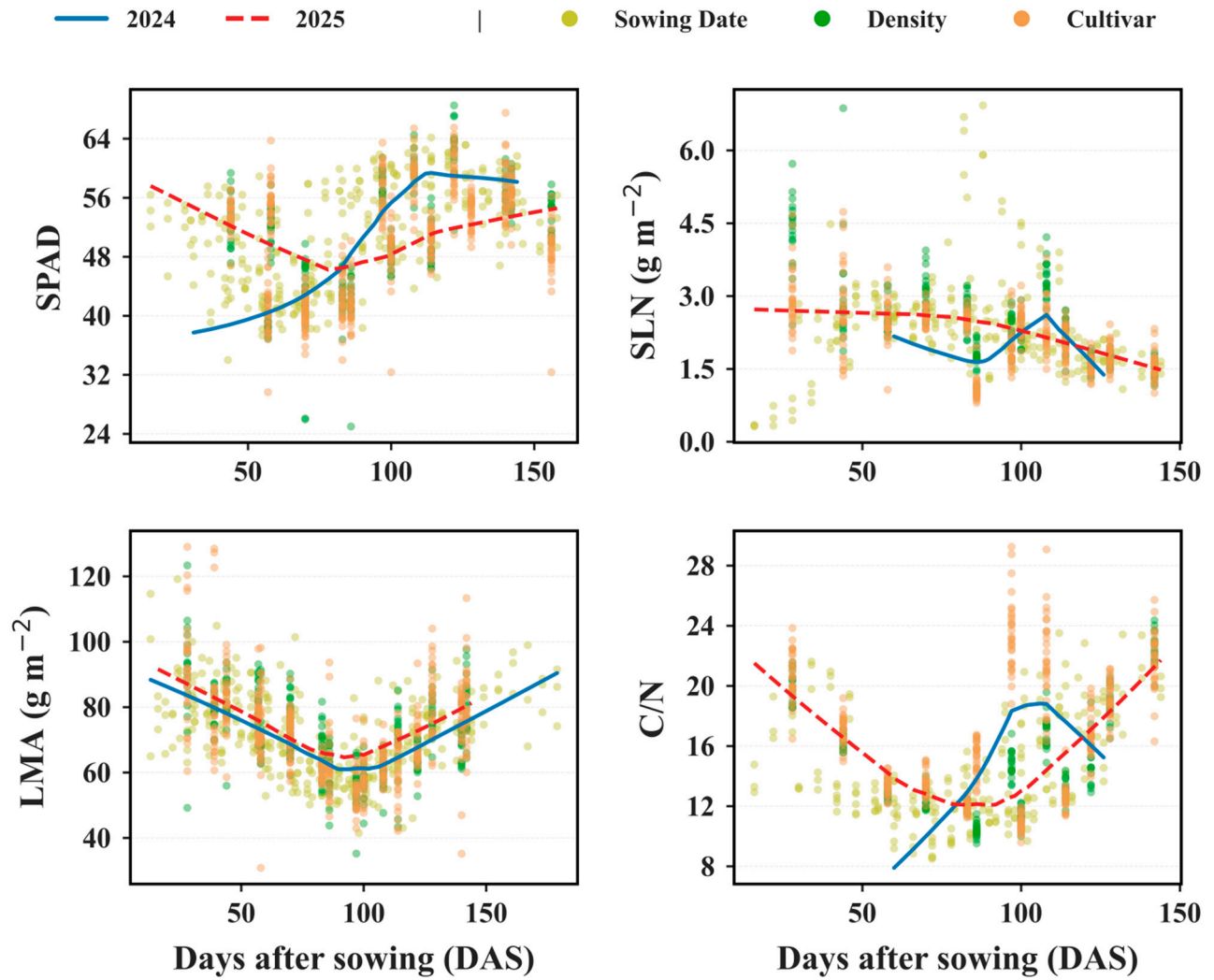


Figure S2. Temporal dynamics of cotton leaf functional traits, including leaf mass per area (LMA), carbon-to-nitrogen ratio (C/N), specific leaf nitrogen (SLN), and relative chlorophyll content (SPAD), throughout the growing season. Scatter points represent individual measurements at different days after sowing (DAS). The curves indicate temporal trends fitted using locally estimated scatterplot smoothing (LOESS) for the 2024 (solid lines) and 2025 (dashed lines) growing seasons.

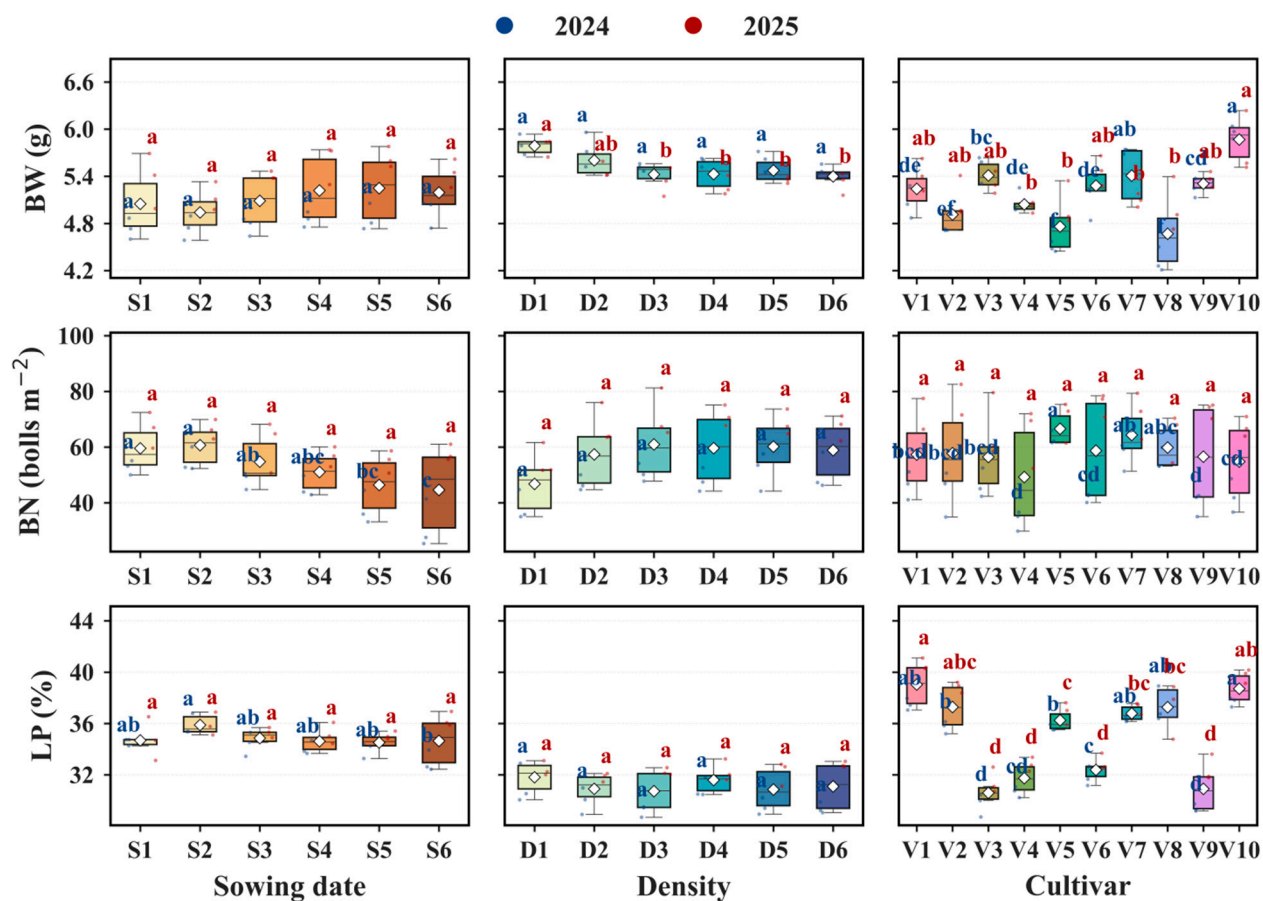


Figure S3. Impacts of agronomic management and genetic variation on cotton yield components including boll number per unit area (BN), boll weight (BW), and lint percentage (LP). Different lowercase letters above the boxplots indicate significant differences at $P < 0.05$ based on Tukey's HSD test.