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Supplementary Material: Predicting Grain Yield and Popping Expansion in Native Peruvian Popcorn and Purple-Kernel Hybrids Using Multitemporal UAV-Derived Multispectral and Textural Indices

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Abstract: This supplementary document accompanies the main manuscript and contains: detailed soil and water characterization (Table S1), MicaSense sensor specifications (Table S2), genotype-stratified machine-learning performance grids for grain yield and popping expansion across three predictor sets (Tables S3–S8), and supporting figures including the UAV platform (Figure S1), Pearson correlation matrices separated by predictor group (Figures S2–S3) and observed-vs-predicted scatter plots stratified by genetic group (Figures S4–S7).

Keywords: UAV; GLCM texture; machine learning; grain yield; popping expansion; purple maize; phenology

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This supplementary document contains:

- **Tables S1–S8** — soil/water characterization, MicaSense bands, and LOGO model performance per genetic group × feature set × phenological stage for grain yield and popping expansion.
- **Figures S1–S7** — UAV platform photographs, Pearson correlation matrices (VI, TI) and observed-vs-predicted scatter plots stratified by genetic group.

S1. Soil Profile and Irrigation Water Characterization

Table S1 reports the detailed physicochemical characterization of the soil profile (0–40 cm) and the irrigation water quality at the AER–UNALM experimental site. The substrate is classified as a sandy clay loam with moderate organic matter content (4.32%) and a saline electrical conductivity (5.17 dS m^{-1}); the irrigation water falls in the C2–S1 Riverside class (medium salinity, low sodium).

Table S1. Detailed physicochemical characterization of the soil profile (0–40 cm) and irrigation water quality at the AER–UNALM experimental site.

Parameter	Unit	Value
Soil Physical Properties		
Texture Class	–	Sandy Clay Loam
Sand / Silt / Clay	%	54 / 19 / 27
Bulk Density (ρ_b)	g cm^{-3}	1.41
Particle Density (ρ_s)	g cm^{-3}	2.67
Total Porosity (ϕ)	%	47.2
Field Capacity (θ_{FC})	cm^3 cm^{-3}	0.2976
Permanent Wilting Point (θ_{PWP})	cm^3 cm^{-3}	0.1627
Soil Chemical Properties		
pH (1:1)	–	7.33
Electrical Conductivity (EC)	dS m^{-1}	5.17
Organic Matter (OM)	%	4.32
Cation Exchange Capacity (CEC)	meq 100 g^{-1}	11.89
Available Phosphorus (P)	ppm	12
Exchangeable Potassium (K)	ppm	376
Calcium (Ca^{2+})	meq kg^{-1}	180.5
Magnesium (Mg^{2+})	meq kg^{-1}	28.1
Sodium (Na^{+})	meq kg^{-1}	2.5
ESP / SAR	% / –	1.14 / 0.08
Heavy Metals (Pb / Cr)	ppm	14.82 / 13.50
Irrigation Water Quality		
Classification (Riverside)	–	C2–S1
pH	–	6.95
Electrical Conductivity (EC_w)	dS m^{-1}	0.47
Sum of Cations / Anions	meq L^{-1}	4.21 / 3.87
Sodium Adsorption Ratio (SAR)	(mmol L^{-1})$^{0.5}$	0.98



Figure S1. UAV platform and sensors used for data acquisition. (**a**) DJI Matrice 300 RTK; (**b**) DJI Zenmuse H20T RGB/thermal camera; and (**c**) MicaSense RedEdge-MX five-band multispectral sensor and calibration panel.

S2. MicaSense RedEdge-MX Spectral Bands

Table S2 summarizes the wavelength ranges of the five spectral bands of the MicaSense RedEdge-MX multispectral sensor used in this study.

Table S2. Wavelength bands of the MicaSense RedEdge-MX multispectral sensor.

Band	Wavelength range
Blue	459–491 nm
Green	546.5–573.5 nm
Red	661–675 nm
Red-edge	711–723 nm
Near-infrared	813.5–870.5 nm

S3. Genotype-Stratified Yield Prediction — VI Only

Table S3 reports the performance of six regression models (MLR, SVR-Linear, SVR-rbf, PLSR, RF, XGBoost) for grain yield prediction using vegetation indices only (VI), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55) at the three priority phenological stages (early grain, grain filling 1 and maturity).

Table S3. Performance of machine-learning models for grain yield prediction using vegetation indices only (VI; LOGO), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55). Three phenological stages. Models sorted by R^2 within each stage. Bold indicates best performance per stage.

Stage	Model	n	n feat.	Selected Features	R^2	RMSE	rRMSE (%)
Hybrid (n = 25)							
Early grain (96 DAS)	MLR	25	6	NDVI, DVI, SR, EVI2, GNDVI, NDRE	0.362	1.2121	19.8
	SVR-Linear	25	4	**NDVI, DVI, OSAVI, GNDVI**	**0.410**	**1.1657**	**19.0**
	SVR-rbf	25	3	NDVI, DVI, EVI2	0.230	1.3318	21.7
	PLSR	25	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.353	1.2202	19.9
	RF	25	3	EVI2, OSAVI, GNDVI	0.032	1.4926	24.4
	XGBoost	25	7	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, SCCCI	0.243	1.3201	21.5
Grain filling 1 (102 DAS)	MLR	25	2	SR, GNDVI	0.069	1.4639	23.9
	SVR-Linear	25	4	**NDVI, DVI, OSAVI, GNDVI**	**0.379**	**1.1953**	**19.5**
	SVR-rbf	25	2	SR, GNDVI	0.184	1.3702	22.4
	PLSR	25	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.100	1.4394	23.5
	RF	25	3	NDVI, DVI, GNDVI	−0.006	1.5218	24.8
	XGBoost	25	6	NDVI, DVI, EVI2, OSAVI, GNDVI, NDRE	0.031	1.4933	24.4
Maturity (117 DAS)	MLR	25	3	NDVI, GNDVI, SCCCI	0.293	1.2758	20.8
	SVR-Linear	25	4	NDVI, GNDVI, NDRE, SCCCI	0.360	1.2137	19.8
	SVR-rbf	25	2	**NDVI, SCCCI**	**0.474**	**1.1001**	**18.0**
	PLSR	25	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.220	1.3399	21.9
	RF	25	1	SCCCI	0.232	1.3293	21.7
	XGBoost	25	6	SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	−0.170	1.6407	26.8
PPCN (n = 55)							
Early grain (96 DAS)	MLR	55	3	DVI, OSAVI, SCCCI	0.271	1.0847	40.5
	SVR-Linear	55	2	DVI, SCCCI	0.254	1.0972	41.0
	SVR-rbf	55	5	NDVI, EVI2, GNDVI, NDRE, SCCCI	0.273	1.0830	40.5
	PLSR	55	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.235	1.1106	41.5
	RF	55	5	NDVI, OSAVI, GNDVI, NDRE, SCCCI	0.170	1.1571	43.2
	XGBoost	55	8	**NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI**	**0.296**	**1.0656**	**39.8**
Grain filling 1 (102 DAS)	MLR	55	3	DVI, SR, SCCCI	0.279	1.0782	40.3
	SVR-Linear	55	4	DVI, SR, EVI2, SCCCI	0.318	1.0492	39.2
	SVR-rbf	55	2	**DVI, GNDVI**	**0.318**	**1.0491**	**39.2**
	PLSR	55	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.251	1.0988	41.1
	RF	55	3	DVI, SR, GNDVI	0.273	1.0826	40.5
	XGBoost	55	3	DVI, SR, GNDVI	0.269	1.0858	40.6
Maturity (117 DAS)	MLR	55	6	NDVI, DVI, SR, OSAVI, GNDVI, SCCCI	0.266	1.0878	40.6
	SVR-Linear	55	3	OSAVI, GNDVI, SCCCI	0.205	1.1327	42.3
	SVR-rbf	55	1	SCCCI	0.211	1.1282	42.2
	PLSR	55	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.267	1.0877	40.6
	RF	55	4	**DVI, EVI2, OSAVI, SCCCI**	**0.316**	**1.0503**	**39.2**
	XGBoost	55	5	NDVI, DVI, EVI2, OSAVI, SCCCI	0.094	1.2091	45.2

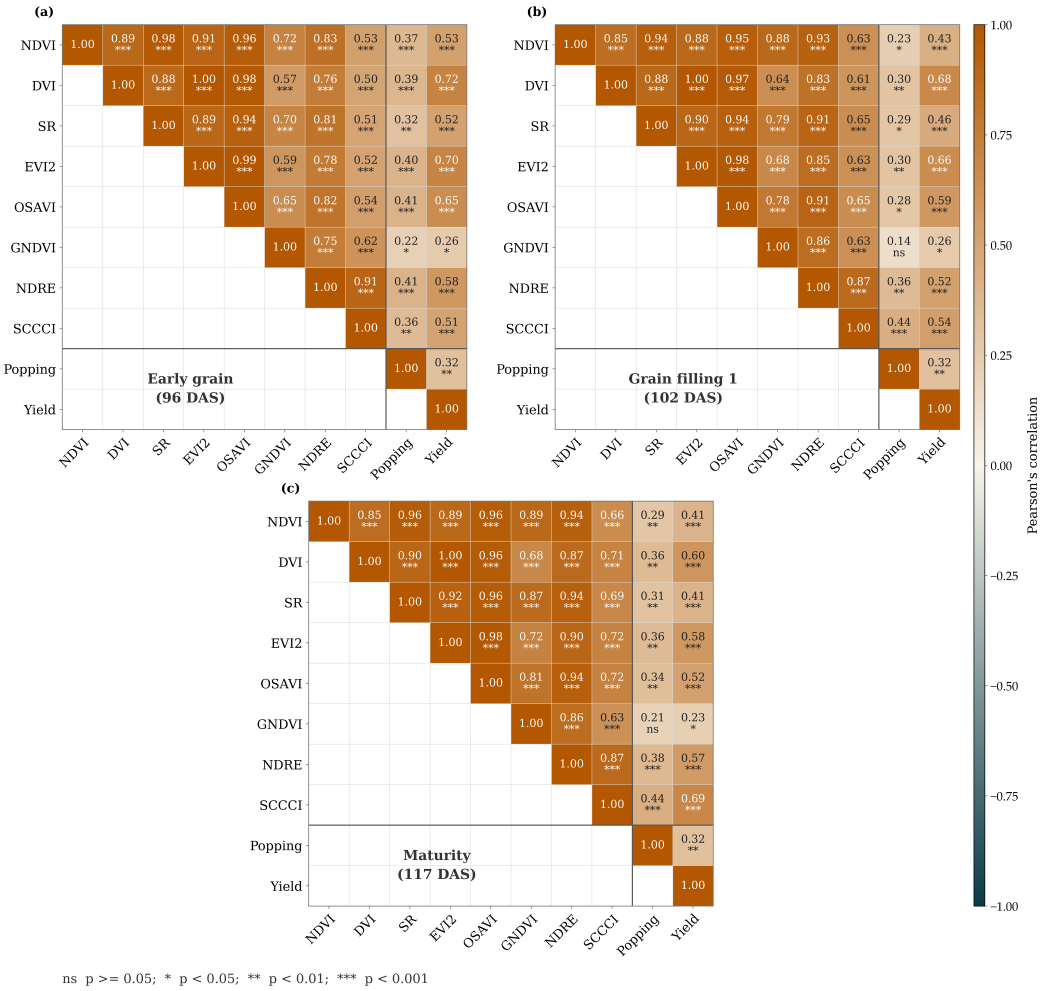


Figure S2. Pearson correlation matrices among vegetation indices (VI) and target traits (popping expansion volume and grain yield) at the (**a**) Early grain (96 DAS), (**b**) Grain filling 1 (102 DAS) and (**c**) Maturity (117 DAS) stages. Significance levels: ns ($p \geq 0.05$), * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$); n = 80 subplots per stage.

S4. Genotype-Stratified Yield Prediction — TI Only

Table S4 reports the LOGO performance of the six regression models using texture indices only (TI) for grain yield prediction, stratified by genetic group at the three priority phenological stages. The associated TI correlation matrices are shown in Figure S3.

Table S4. Performance of machine-learning models for grain yield prediction using texture indices only (TI; LOGO), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55). Three phenological stages. Models sorted by R^2 within each stage. Bold indicates best performance per stage.

Stage	Model	n	n feat.	Selected Features	R^2	RMSE	rRMSE (%)
Hybrid (n = 25)							
Early grain (96 DAS)	MLR	25	1	Contrast	−0.152	1.6284	26.6
	SVR-Linear	25	1	Contrast	−0.178	1.6463	26.9
	SVR-rbf	25	1	**Entropy**	**0.355**	**1.2181**	**19.9**
	PLSR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.242	1.6909	27.6
	RF	25	2	Entropy, Homogeneity	0.164	1.3870	22.6
	XGBoost	25	4	Energy, Entropy, Correlation, Homogeneity	0.057	1.4737	24.0
Grain filling 1 (102 DAS)	MLR	25	1	Homogeneity	−0.135	1.6162	26.4
	SVR-Linear	25	3	Energy, Entropy, Homogeneity	−0.069	1.5685	25.6
	SVR-rbf	25	1	Energy	0.161	1.3898	22.7
	PLSR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.138	1.6183	26.4
	RF	25	1	**Energy**	**0.190**	**1.3659**	**22.3**
	XGBoost	25	4	Energy, Entropy, Homogeneity, Contrast	−0.119	1.6047	26.2
Maturity (117 DAS)	MLR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.196	1.6592	27.1
	SVR-Linear	25	1	Correlation	−0.092	1.5853	25.9
	SVR-rbf	25	2	**Entropy, Homogeneity**	**0.064**	**1.4678**	**24.0**
	PLSR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.196	1.6592	27.1
	RF	25	1	Energy	−0.235	1.6862	27.5
	XGBoost	25	2	Correlation, Contrast	−0.170	1.6408	26.8
PPCN (n = 55)							
Early grain (96 DAS)	MLR	55	3	Entropy, Homogeneity, Contrast	0.285	1.0739	40.1
	SVR-Linear	55	2	Energy, Contrast	0.284	1.0744	40.1
	SVR-rbf	55	1	Correlation	0.218	1.1229	42.0
	PLSR	55	5	Energy, Entropy, Correlation, Homogeneity, Contrast	0.251	1.0991	41.1
	RF	55	3	Entropy, Correlation, Homogeneity	0.292	1.0684	39.9
	XGBoost	55	5	**Energy, Entropy, Correlation, Homogeneity, Contrast**	**0.320**	**1.0470**	**39.1**
Grain filling 1 (102 DAS)	**MLR**	55	1	**Energy**	**−0.044**	**1.2978**	**48.5**
	SVR-Linear	55	1	Correlation	−0.112	1.3395	50.1
	SVR-rbf	55	1	Correlation	−0.121	1.3447	50.2
	PLSR	55	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.059	1.3072	48.8
	RF	55	2	Energy, Entropy	−0.147	1.3603	50.8
	XGBoost	55	4	Energy, Entropy, Correlation, Contrast	−0.101	1.3327	49.8
Maturity (117 DAS)	MLR	55	3	Energy, Homogeneity, Contrast	0.099	1.2057	45.1
	SVR-Linear	55	4	Energy, Entropy, Homogeneity, Contrast	0.051	1.2372	46.2
	SVR-rbf	55	1	**Energy**	**0.149**	**1.1720**	**43.8**
	PLSR	55	5	Energy, Entropy, Correlation, Homogeneity, Contrast	0.070	1.2248	45.8
	RF	55	4	Energy, Correlation, Homogeneity, Contrast	0.075	1.2218	45.7
	XGBoost	55	4	Energy, Entropy, Correlation, Contrast	−0.010	1.2761	47.7

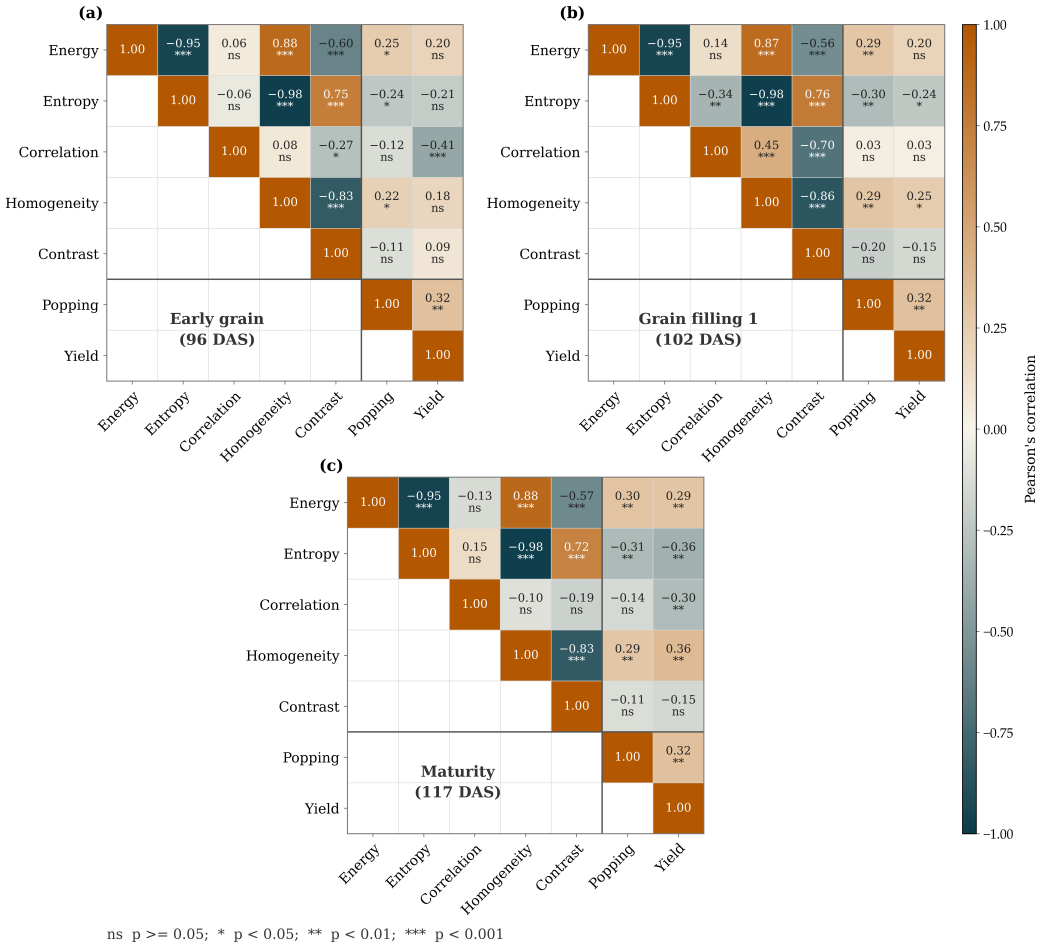


Figure S3. Pearson correlation matrices among texture indices (TI) and target traits (popping expansion volume and grain yield) at the (**a**) Early grain (96 DAS), (**b**) Grain filling 1 (102 DAS) and (**c**) Maturity (117 DAS) stages. Significance levels: ns ($p \geq 0.05$), * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$); n = 80 subplots per stage.

S5. Genotype-Stratified Yield Prediction — VI + TI Combined

Table S5 reports the LOGO performance of the six regression models using the combined VI + TI predictor set for grain yield prediction, stratified by genetic group at the three priority phenological stages. Figures S4 and S5 show the corresponding observed-vs-predicted scatter plots for the VI-only and TI-only subsets.

Table S5. Performance of machine-learning models for grain yield prediction using the combined VI + TI predictor set (LOGO), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55). Three phenological stages. Models sorted by R^2 within each stage. Bold indicates best performance per stage.

Stage	Model	n	n feat.	Selected Features	R^2	RMSE	rRMSE (%)
Hybrid (n = 25)							
Early grain (96 DAS)	**MLR**	25	5	**NDVI, DVI, SR, OSAVI, Correlation**	**0.498**	**1.0753**	**17.5**
	SVR-Linear	25	6	NDVI, DVI, EVI2, OSAVI, GNDVI, Contrast	0.170	1.3820	22.5
	SVR-rbf	25	1	Entropy	0.355	1.2181	19.9
	PLSR	25	13	All 13 (VI+TI)	0.032	1.4931	24.4
	RF	25	3	SR, GNDVI, Entropy	0.299	1.2700	20.7
	XGBoost	25	8	NDVI, DVI, OSAVI, GNDVI, SCCCI, Entropy, Correlation, Homogeneity	0.240	1.3224	21.6
Grain filling 1 (102 DAS)	MLR	25	2	SR, GNDVI	0.069	1.4639	23.9
	SVR-Linear	25	6	NDVI, DVI, EVI2, OSAVI, GNDVI, Homogeneity	0.381	1.1933	19.5
	SVR-rbf	25	1	Energy	0.161	1.3898	22.7
	PLSR	25	13	All 13 (VI+TI)	−0.132	1.6143	26.3
	RF	25	3	OSAVI, Energy, Contrast	0.069	1.4640	23.9
	XGBoost	25	5	**NDVI, GNDVI, Energy, Entropy, Contrast**	**0.394**	**1.1813**	**19.3**
Maturity (117 DAS)	MLR	25	4	NDVI, GNDVI, SCCCI, Energy	0.413	1.1621	19.0
	SVR-Linear	25	11	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI, Energy, Entropy, Homogeneity	0.271	1.2958	21.1
	SVR-rbf	25	2	**NDVI, SCCCI**	**0.474**	**1.1001**	**18.0**
	PLSR	25	13	All 13 (VI+TI)	0.037	1.4887	24.3
	RF	25	1	SCCCI	0.232	1.3293	21.7
	XGBoost	25	3	SCCCI, Entropy, Homogeneity	0.215	1.3440	21.9
PPCN (n = 55)							
Early grain (96 DAS)	MLR	55	5	DVI, OSAVI, SCCCI, Energy, Contrast	0.371	1.0077	37.7
	SVR-Linear	55	8	NDVI, DVI, EVI2, OSAVI, Energy, Entropy, Homogeneity, Contrast	0.302	1.0610	39.6
	SVR-rbf	55	7	EVI2, GNDVI, NDRE, SCCCI, Energy, Correlation, Contrast	0.368	1.0098	37.7
	PLSR	55	13	All 13 (VI+TI)	0.277	1.0800	40.4
	RF	55	3	Entropy, Correlation, Homogeneity	0.292	1.0684	39.9
	XGBoost	55	5	**GNDVI, NDRE, Entropy, Correlation, Homogeneity**	**0.404**	**0.9807**	**36.6**
Grain filling 1 (102 DAS)	MLR	55	4	NDVI, DVI, SCCCI, Contrast	0.422	0.9656	36.1
	SVR-Linear	55	10	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, SCCCI, Energy, Correlation, Contrast	0.387	0.9943	37.2
	SVR-rbf	55	5	**DVI, GNDVI, SCCCI, Entropy, Correlation**	**0.432**	**0.9576**	**35.8**
	PLSR	55	13	All 13 (VI+TI)	0.373	1.0057	37.6
	RF	55	9	DVI, SR, EVI2, GNDVI, NDRE, SCCCI, Entropy, Correlation, Contrast	0.277	1.0803	40.4
	XGBoost	55	8	DVI, SR, EVI2, GNDVI, NDRE, SCCCI, Entropy, Correlation	0.343	1.0293	38.5
Maturity (117 DAS)	MLR	55	7	NDVI, DVI, SR, OSAVI, GNDVI, SCCCI, Contrast	0.269	1.0863	40.6
	SVR-Linear	55	3	OSAVI, GNDVI, SCCCI	0.205	1.1327	42.3
	SVR-rbf	55	4	SCCCI, Energy, Homogeneity, Contrast	0.282	1.0765	40.2
	PLSR	55	13	All 13 (VI+TI)	0.239	1.1083	41.4
	RF	55	3	**SCCCI, Homogeneity, Contrast**	**0.361**	**1.0155**	**37.9**
	XGBoost	55	4	NDVI, EVI2, SCCCI, Contrast	0.155	1.1673	43.6

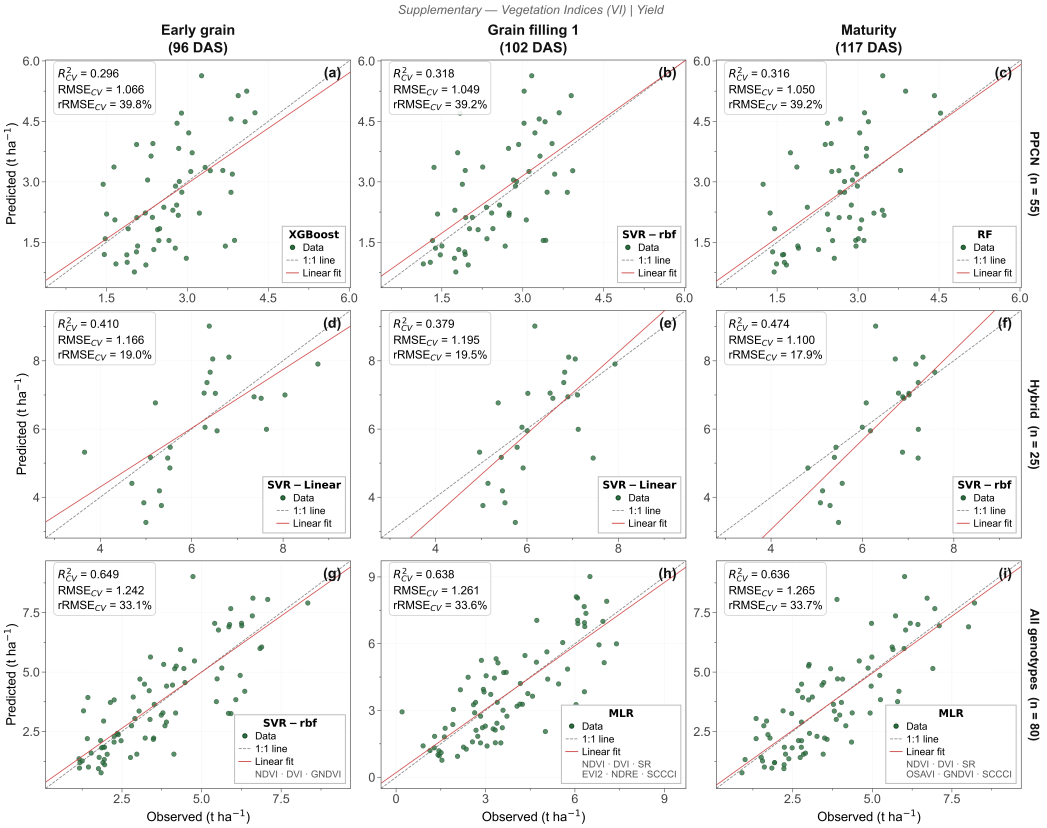


Figure S4. Observed vs. predicted grain yield for the best-performing model at each phenological stage (columns: early grain, 96 DAS; grain filling 1, 102 DAS; maturity, 117 DAS) and genetic group (rows: PPCN, n = 55; Hybrid, n = 25; All genotypes, n = 80), using vegetation indices only (VI). Each panel displays R^2_{CV}, RMSE$_{CV}$, rRMSE$_{CV}$, the selected algorithm and its SFS features. Dashed line indicates the 1:1 reference; solid line shows the linear fit. Performance metrics: R^2_{CV} = leave-one-lysimeter-out coefficient of determination; RMSE$_{CV}$ = root mean square error (t ha^{-1}); rRMSE$_{CV}$ = relative RMSE as percentage of observed mean.

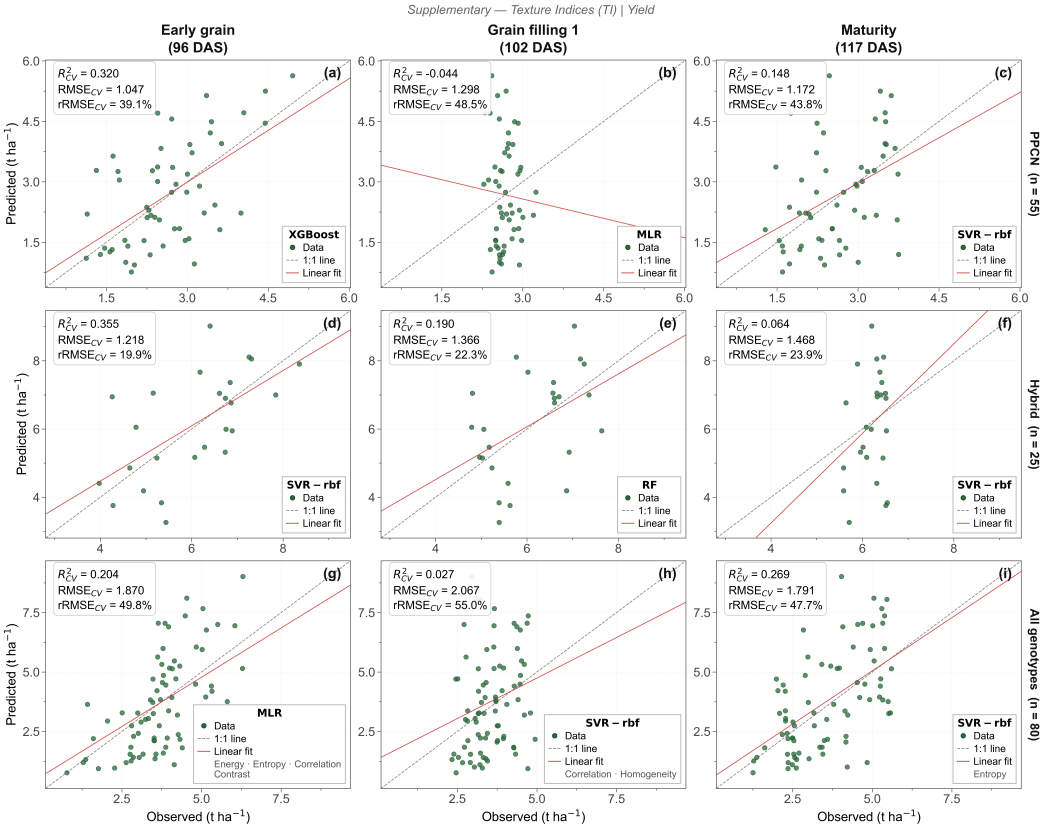


Figure S5. Observed vs. predicted grain yield for the best-performing model at each phenological stage (columns: early grain, 96 DAS; grain filling 1, 102 DAS; maturity, 117 DAS) and genetic group (rows: PPCN, n = 55; Hybrid, n = 25; All genotypes, n = 80), using texture indices only (TI). Each panel displays R^2_{CV}, RMSE$_{CV}$, rRMSE$_{CV}$, the selected algorithm and its SFS features. Dashed line indicates the 1:1 reference; solid line shows the linear fit. Performance metrics: R^2_{CV} = leave-one-lysimeter-out coefficient of determination; RMSE$_{CV}$ = root mean square error (t ha^{-1}); rRMSE$_{CV}$ = relative RMSE as percentage of observed mean.

S6. Genotype-Stratified Popping Expansion Prediction — VI Only

Table S6 reports the LOGO performance of the six regression models using vegetation indices only (VI) for popping expansion volume prediction, stratified by genetic group at the three priority phenological stages. Figure S6 shows the corresponding observed-vs-predicted scatter plots.

Table S6. Performance of machine-learning models for popping expansion volume prediction using vegetation indices only (VI; LOGO), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55). Three phenological stages. Models sorted by R^2 within each stage. Bold indicates best performance per stage.

Stage	Model	n	n feat.	Selected Features	R^2	RMSE	rRMSE (%)
Hybrid (n = 25)							
Early grain (96 DAS)	MLR	25	1	NDVI	−0.161	4.6761	25.4
	SVR-Linear	25	1	**DVI**	**−0.039**	**4.4232**	**24.0**
	SVR-rbf	25	2	NDVI, SR	−0.166	4.6860	25.5
	PLSR	25	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	−0.183	4.7212	25.7
	RF	25	1	DVI	−0.236	4.8261	26.2
	XGBoost	25	3	DVI, EVI2, SCCCI	−0.100	4.5527	24.7
Grain filling 1 (102 DAS)	MLR	25	2	SR, EVI2	−0.279	4.9079	26.7
	SVR-Linear	25	1	EVI2	−0.014	4.3697	23.8
	SVR-rbf	25	1	**NDVI**	**0.156**	**3.9864**	**21.7**
	PLSR	25	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	−0.276	4.9025	26.6
	RF	25	1	GNDVI	0.042	4.2489	23.1
	XGBoost	25	4	NDVI, OSAVI, GNDVI, SCCCI	−0.114	4.5811	24.9
Maturity (117 DAS)	MLR	25	1	SR	−0.168	4.6899	25.5
	SVR-Linear	25	1	**DVI**	**−0.035**	**4.4158**	**24.0**
	SVR-rbf	25	1	NDRE	−0.115	4.5822	24.9
	PLSR	25	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	−0.188	4.7307	25.7
	RF	25	1	SR	−0.436	5.2005	28.3
	XGBoost	25	5	DVI, SR, OSAVI, GNDVI, NDRE	−0.097	4.5457	24.7
PPCN (n = 55)							
Early grain (96 DAS)	MLR	55	1	NDRE	0.073	3.1455	20.1
	SVR-Linear	55	1	EVI2	0.097	3.1057	19.8
	SVR-rbf	55	2	**NDVI, GNDVI**	**0.262**	**2.8068**	**17.9**
	PLSR	55	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.073	3.1456	20.1
	RF	55	4	NDVI, SR, GNDVI, SCCCI	0.193	2.9353	18.8
	XGBoost	55	3	SR, OSAVI, GNDVI	0.246	2.8379	18.1
Grain filling 1 (102 DAS)	MLR	55	1	SCCCI	0.124	3.0577	19.5
	SVR-Linear	55	1	SCCCI	0.142	3.0275	19.3
	SVR-rbf	55	2	**GNDVI, SCCCI**	**0.202**	**2.9198**	**18.7**
	PLSR	55	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.067	3.1571	20.2
	RF	55	4	NDVI, GNDVI, NDRE, SCCCI	0.075	3.1435	20.1
	XGBoost	55	5	DVI, SR, GNDVI, NDRE, SCCCI	0.044	3.1956	20.4
Maturity (117 DAS)	MLR	55	1	SCCCI	0.158	2.9978	19.2
	SVR-Linear	55	2	DVI, SCCCI	0.133	3.0425	19.4
	SVR-rbf	55	3	**NDVI, SR, SCCCI**	**0.230**	**2.8683**	**18.3**
	PLSR	55	8	NDVI, DVI, SR, EVI2, OSAVI, GNDVI, NDRE, SCCCI	0.081	3.1325	20.0
	RF	55	5	NDVI, SR, EVI2, OSAVI, SCCCI	0.200	2.9220	18.7
	XGBoost	55	2	NDVI, GNDVI	−0.040	3.3322	21.3

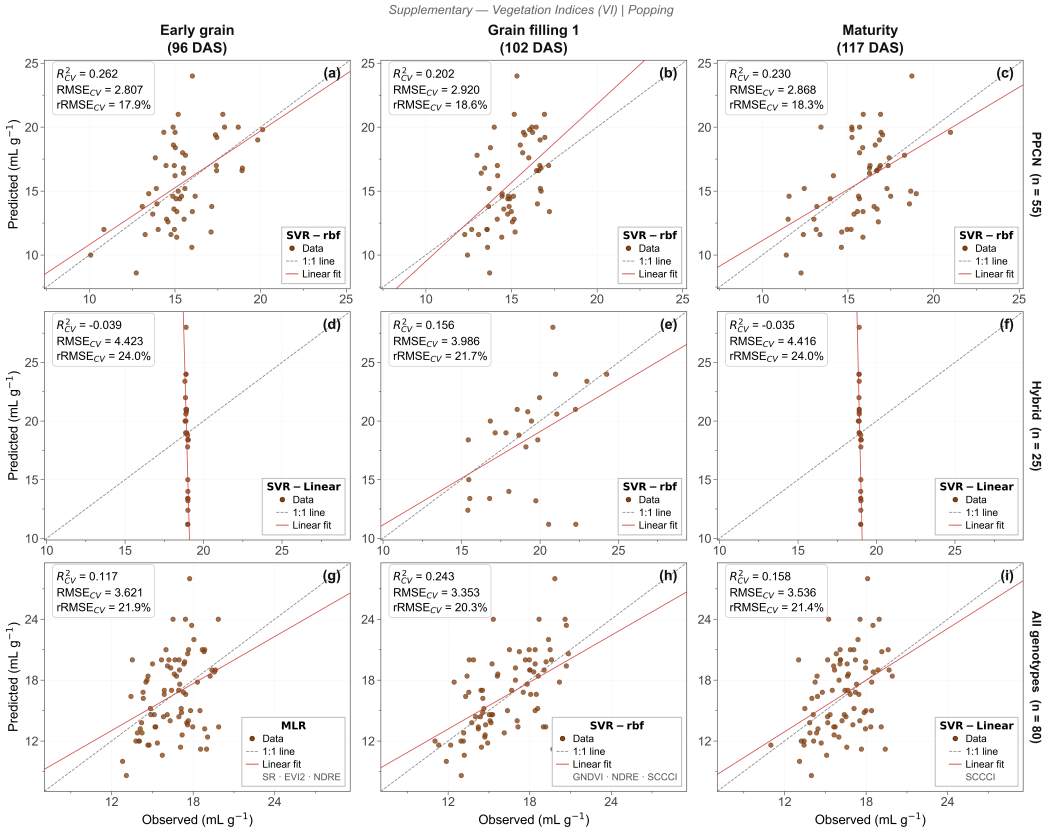


Figure S6. Observed vs. predicted popping expansion volume for the best-performing model at each phenological stage (columns: early grain, 96 DAS; grain filling 1, 102 DAS; maturity, 117 DAS) and genetic group (rows: PPCN, n = 55; Hybrid, n = 25; All genotypes, n = 80), using vegetation indices only (VI). Each panel displays R^2_{CV}, RMSE$_{CV}$, rRMSE$_{CV}$, the selected algorithm and its SFS features. Dashed line indicates the 1:1 reference; solid line shows the linear fit. Performance metrics: R^2_{CV} = leave-one-lysimeter-out coefficient of determination; RMSE$_{CV}$ = root mean square error (mL g^{-1}); rRMSE$_{CV}$ = relative RMSE as percentage of observed mean.

S7. Genotype-Stratified Popping Expansion Prediction — TI Only

Table S7 reports the LOGO performance of the six regression models using texture indices only (TI) for popping expansion volume prediction, stratified by genetic group at the three priority phenological stages. Figure S7 shows the corresponding observed-vs-predicted scatter plots.

Table S7. Performance of machine-learning models for popping expansion volume prediction using texture indices only (TI; LOGO), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55). Three phenological stages. Models sorted by R^2 within each stage. Bold indicates best performance per stage.

Stage	Model	n	n feat.	Selected Features	R^2	RMSE	rRMSE (%)
Hybrid (n = 25)							
Early grain (96 DAS)	MLR	25	1	Energy	−0.144	4.6432	25.2
	SVR-Linear	25	1	Contrast	−0.043	4.4316	24.1
	SVR-rbf	25	3	**Energy, Entropy, Homogeneity**	**0.022**	**4.2920**	**23.3**
	PLSR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.213	4.7809	26.0
	RF	25	1	Entropy	0.012	4.3138	23.4
	XGBoost	25	2	Energy, Entropy	−0.133	4.6197	25.1
Grain filling 1 (102 DAS)	MLR	25	1	Entropy	−0.066	4.4817	24.4
	SVR-Linear	25	3	Energy, Entropy, Homogeneity	−0.033	4.4110	24.0
	SVR-rbf	25	1	Homogeneity	0.116	4.0809	22.2
	PLSR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.110	4.5734	24.9
	RF	25	1	**Energy**	**0.332**	**3.5487**	**19.3**
	XGBoost	25	2	Entropy, Homogeneity	0.322	3.5736	19.4
Maturity (117 DAS)	MLR	25	1	Energy	−0.057	4.4619	24.3
	SVR-Linear	25	1	Energy	0.058	4.2133	22.9
	SVR-rbf	25	1	**Entropy**	**0.154**	**3.9927**	**21.7**
	PLSR	25	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.112	4.5777	24.9
	RF	25	1	Energy	−0.125	4.6027	25.0
	XGBoost	25	2	Energy, Entropy	0.090	4.1411	22.5
PPCN (n = 55)							
Early grain (96 DAS)	MLR	55	1	Entropy	−0.042	3.3350	21.3
	SVR-Linear	55	1	**Entropy**	**−0.018**	**3.2964**	**21.1**
	SVR-rbf	55	1	Energy	−0.048	3.3448	21.4
	PLSR	55	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.062	3.3679	21.5
	RF	55	1	Contrast	−0.095	3.4195	21.8
	XGBoost	55	3	Energy, Entropy, Homogeneity	−0.034	3.3225	21.2
Grain filling 1 (102 DAS)	MLR	55	1	Energy	−0.044	3.3392	21.3
	SVR-Linear	55	1	Energy	−0.033	3.3214	21.2
	SVR-rbf	55	1	**Energy**	**0.276**	**2.7800**	**17.8**
	PLSR	55	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.066	3.3732	21.5
	RF	55	1	Energy	0.100	3.1001	19.8
	XGBoost	55	3	Energy, Entropy, Homogeneity	−0.089	3.4102	21.8
Maturity (117 DAS)	MLR	55	1	Energy	−0.019	3.2989	21.1
	SVR-Linear	55	3	Energy, Correlation, Homogeneity	−0.099	3.4256	21.9
	SVR-rbf	55	1	Contrast	−0.002	3.2706	20.9
	PLSR	55	5	Energy, Entropy, Correlation, Homogeneity, Contrast	−0.037	3.3277	21.3
	RF	55	3	**Correlation, Homogeneity, Contrast**	**0.034**	**3.2123**	**20.5**
	XGBoost	55	4	Energy, Correlation, Homogeneity, Contrast	−0.065	3.3717	21.5

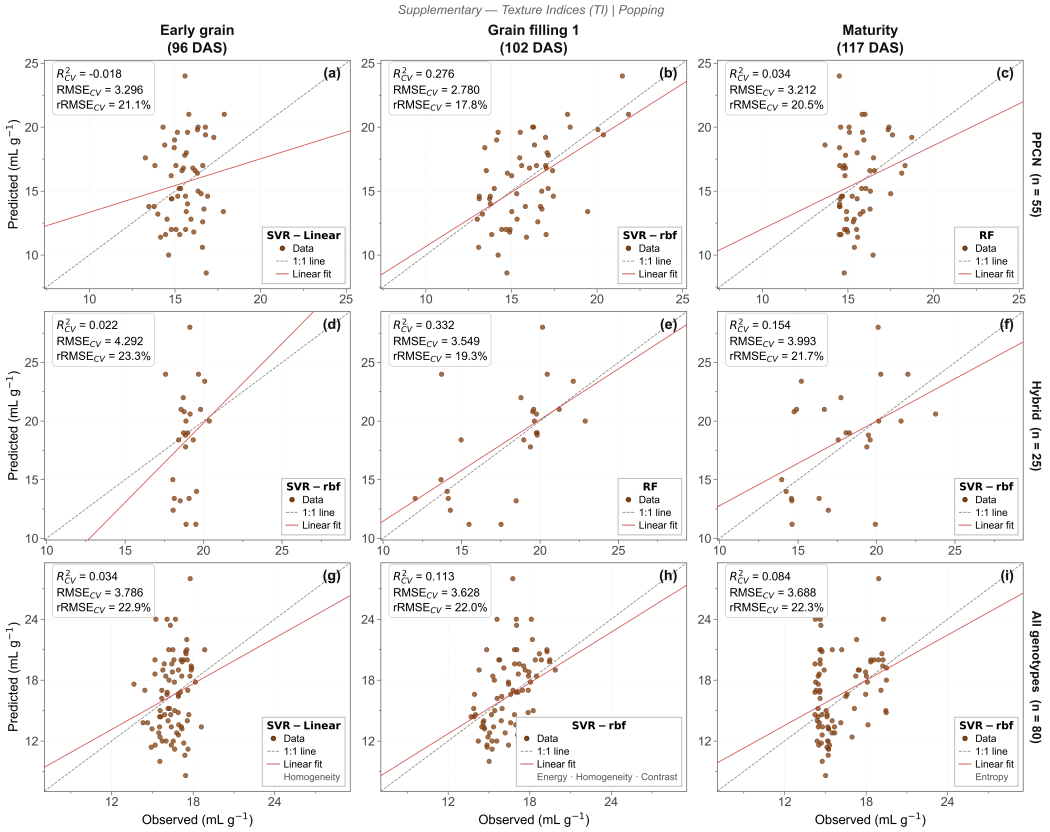


Figure S7. Observed vs. predicted popping expansion volume for the best-performing model at each phenological stage (columns: early grain, 96 DAS; grain filling 1, 102 DAS; maturity, 117 DAS) and genetic group (rows: PPCN, n = 55; Hybrid, n = 25; All genotypes, n = 80), using texture indices only (TI). Each panel displays R^2_{CV}, RMSE$_{CV}$, rRMSE$_{CV}$, the selected algorithm and its SFS features. Dashed line indicates the 1:1 reference; solid line shows the linear fit. Performance metrics: R^2_{CV} = leave-one-lysimeter-out coefficient of determination; RMSE$_{CV}$ = root mean square error (mL g^{-1}); rRMSE$_{CV}$ = relative RMSE as percentage of observed mean.

S8. Genotype-Stratified Popping Expansion Prediction — VI + TI Combined

Table S8 reports the LOGO performance of the six regression models using the combined VI + TI predictor set for popping expansion volume prediction, stratified by genetic group (Hybrid, n = 25; PPCN, n = 55) at the three priority phenological stages.

Table S8. Performance of machine-learning models for popping expansion volume prediction using the combined VI + TI predictor set (LOGO), stratified by genetic group (Hybrid, n = 25; PPCN, n = 55). Three phenological stages. Models sorted by R^2 within each stage. Bold indicates best performance per stage.

Stage	Model	n	n feat.	Selected Features	R^2	RMSE	rRMSE (%)
Hybrid (n = 25)							
Early grain (96 DAS)	MLR	25	1	Energy	−0.144	4.6432	25.2
	SVR-Linear	25	1	DVI	−0.039	4.4232	24.0
	SVR-rbf	25	2	NDVI, SR	−0.166	4.6860	25.5
	PLSR	25	13	All 13 (VI+TI)	−0.227	4.8078	26.1
	RF	25	1	**Entropy**	**0.012**	**4.3138**	**23.4**
	XGBoost	25	3	NDVI, NDRE, Energy	−1.022	6.1717	33.5
Grain filling 1 (102 DAS)	MLR	25	1	Entropy	−0.066	4.4817	24.4
	SVR-Linear	25	4	GNDVI, SCCCI, Entropy, Homogeneity	0.053	4.2241	23.0
	SVR-rbf	25	4	NDVI, OSAVI, GNDVI, Homogeneity	0.317	3.5870	19.5
	PLSR	25	13	All 13 (VI+TI)	−0.218	4.7902	26.0
	RF	25	2	**GNDVI, Energy**	**0.423**	**3.2978**	**17.9**
	XGBoost	25	6	GNDVI, Energy, Entropy, Correlation, Homogeneity, Contrast	0.072	4.1814	22.7
Maturity (117 DAS)	MLR	25	1	Energy	−0.057	4.4619	24.3
	SVR-Linear	25	1	Energy	0.058	4.2133	22.9
	SVR-rbf	25	3	DVI, Energy, Entropy	−0.035	4.4159	24.0
	PLSR	25	13	All 13 (VI+TI)	−0.304	4.9555	26.9
	RF	25	1	Energy	−0.125	4.6027	25.0
	XGBoost	25	2	**Energy, Entropy**	**0.090**	**4.1411**	**22.5**
PPCN (n = 55)							
Early grain (96 DAS)	MLR	55	1	NDRE	0.073	3.1455	20.1
	SVR-Linear	55	1	EVI2	0.097	3.1057	19.8
	SVR-rbf	55	2	**NDVI, GNDVI**	**0.262**	**2.8068**	**17.9**
	PLSR	55	13	All 13 (VI+TI)	0.063	3.1637	20.2
	RF	55	4	NDVI, SR, GNDVI, SCCCI	0.193	2.9353	18.8
	XGBoost	55	3	SR, OSAVI, GNDVI	0.246	2.8379	18.1
Grain filling 1 (102 DAS)	MLR	55	1	SCCCI	0.124	3.0577	19.5
	SVR-Linear	55	1	SCCCI	0.142	3.0275	19.3
	SVR-rbf	55	2	**GNDVI, SCCCI**	**0.202**	**2.9198**	**18.7**
	PLSR	55	13	All 13 (VI+TI)	0.026	3.2245	20.6
	RF	55	1	Energy	0.100	3.1001	19.8
	XGBoost	55	3	NDRE, Energy, Entropy	−0.033	3.3204	21.2
Maturity (117 DAS)	MLR	55	1	SCCCI	0.158	2.9978	19.2
	SVR-Linear	55	2	SCCCI, Correlation	0.096	3.1071	19.8
	SVR-rbf	55	3	NDVI, SR, SCCCI	0.230	2.8683	18.3
	PLSR	55	13	All 13 (VI+TI)	0.003	3.2623	20.8
	RF	55	4	**SR, GNDVI, SCCCI, Homogeneity**	**0.267**	**2.7977**	**17.9**
	XGBoost	55	6	NDVI, GNDVI, NDRE, SCCCI, Correlation, Contrast	0.137	3.0363	19.4