

Figure S1. Preprocessing results of (a) acoustic signals and (b) spectra after denoising using Gaussian filtering (GF), Savitzky-Golay smoothing (SG), and wavelet denoising (WD).

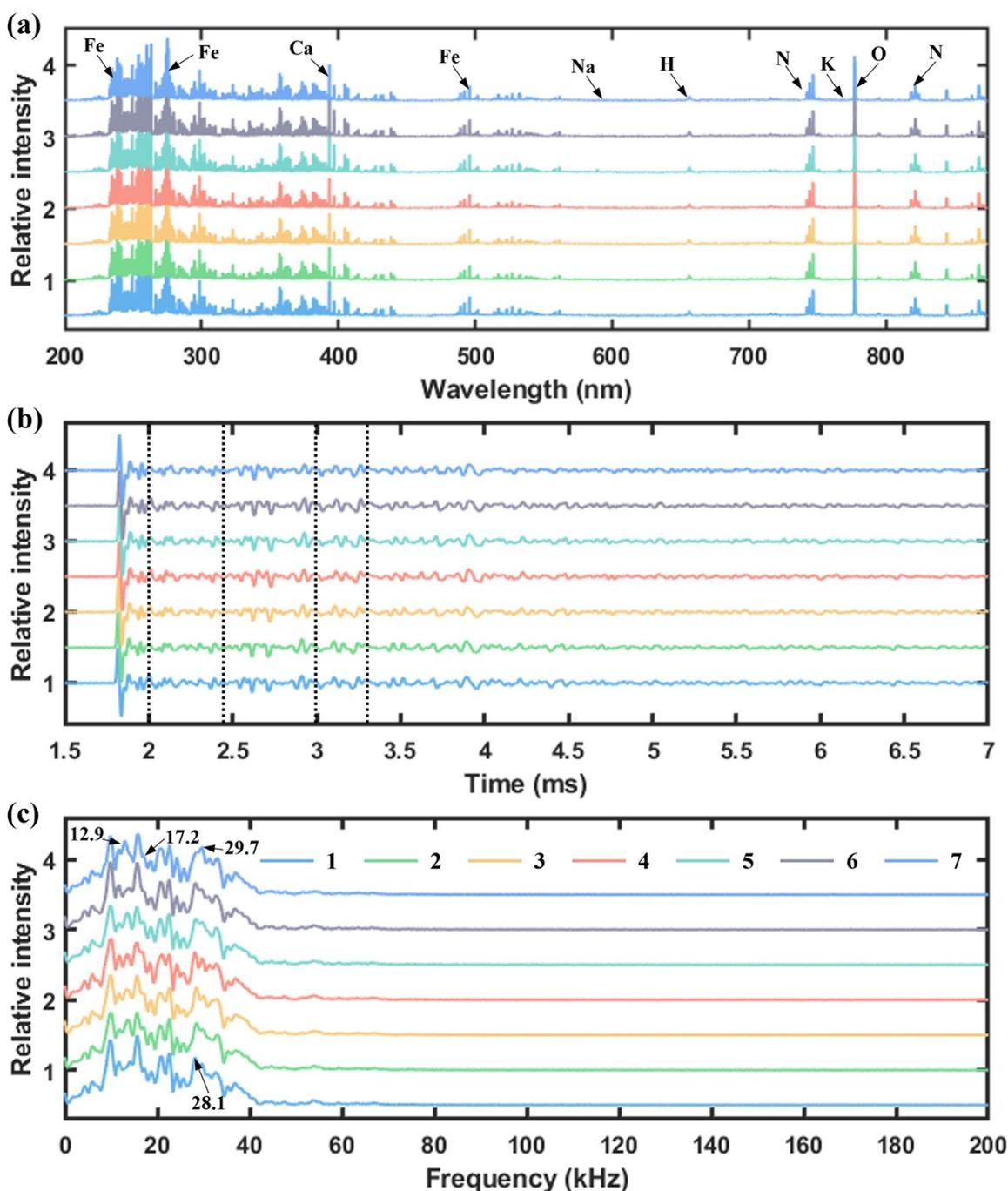


Figure S2. (a) Average spectra, (b) time-domain acoustic signals, and (c) frequency-domain acoustic signals of different samples.

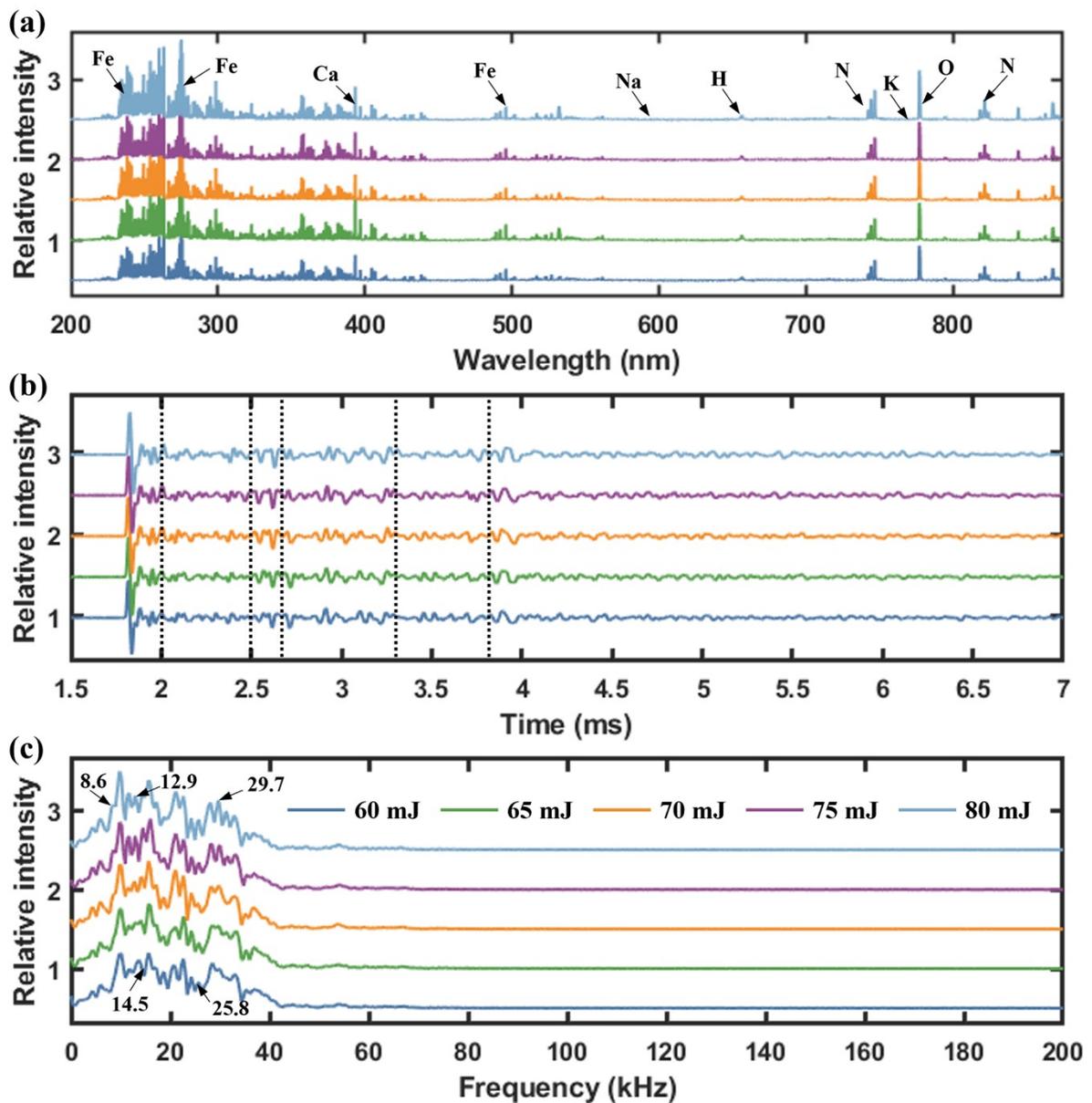


Figure S3. (a) Average spectra, (b) time-domain acoustic signals, and (c) frequency-domain acoustic signals of Sample 1 under different laser energies.

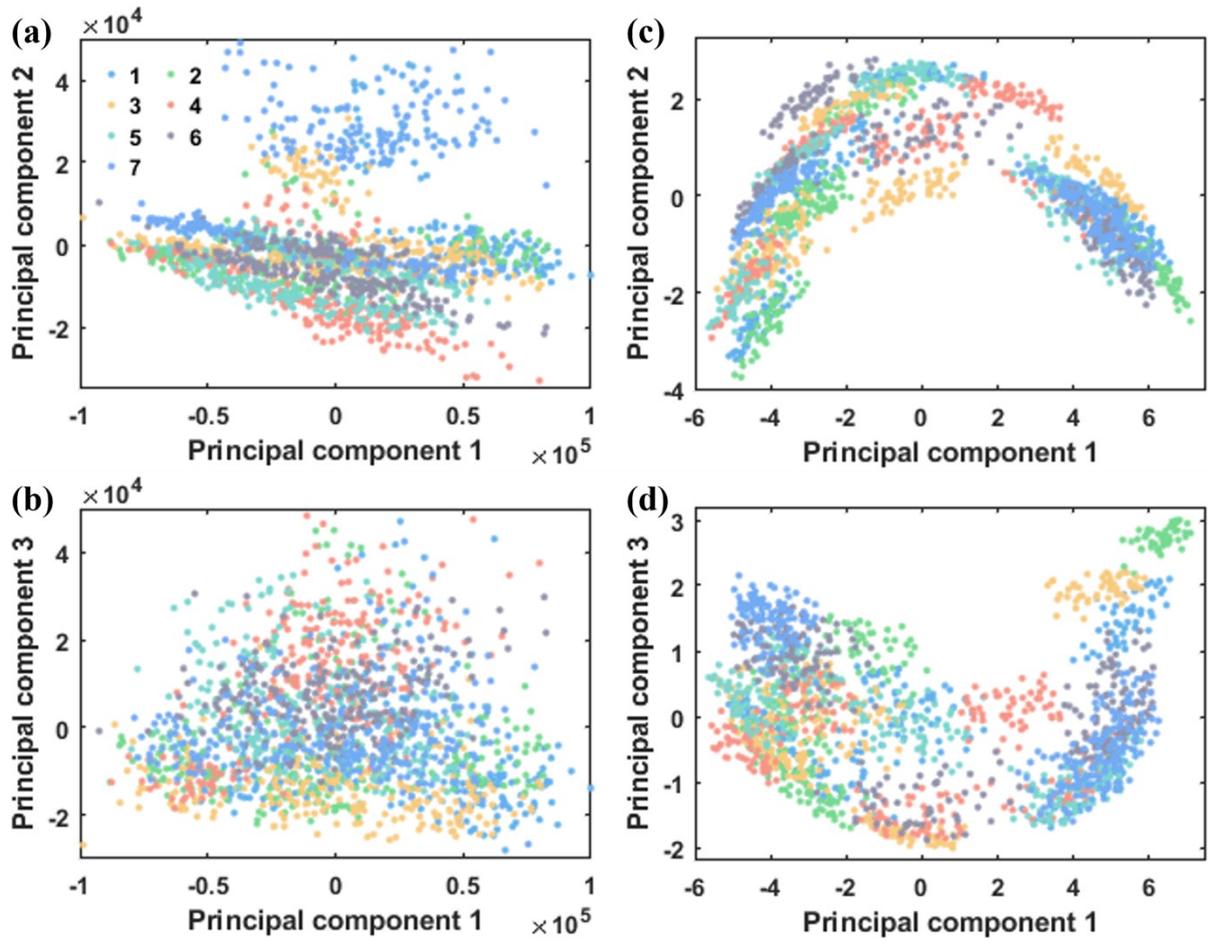


Figure S4. Principal component analysis plots of (a), (b) spectra and (c), (d) acoustic signals.

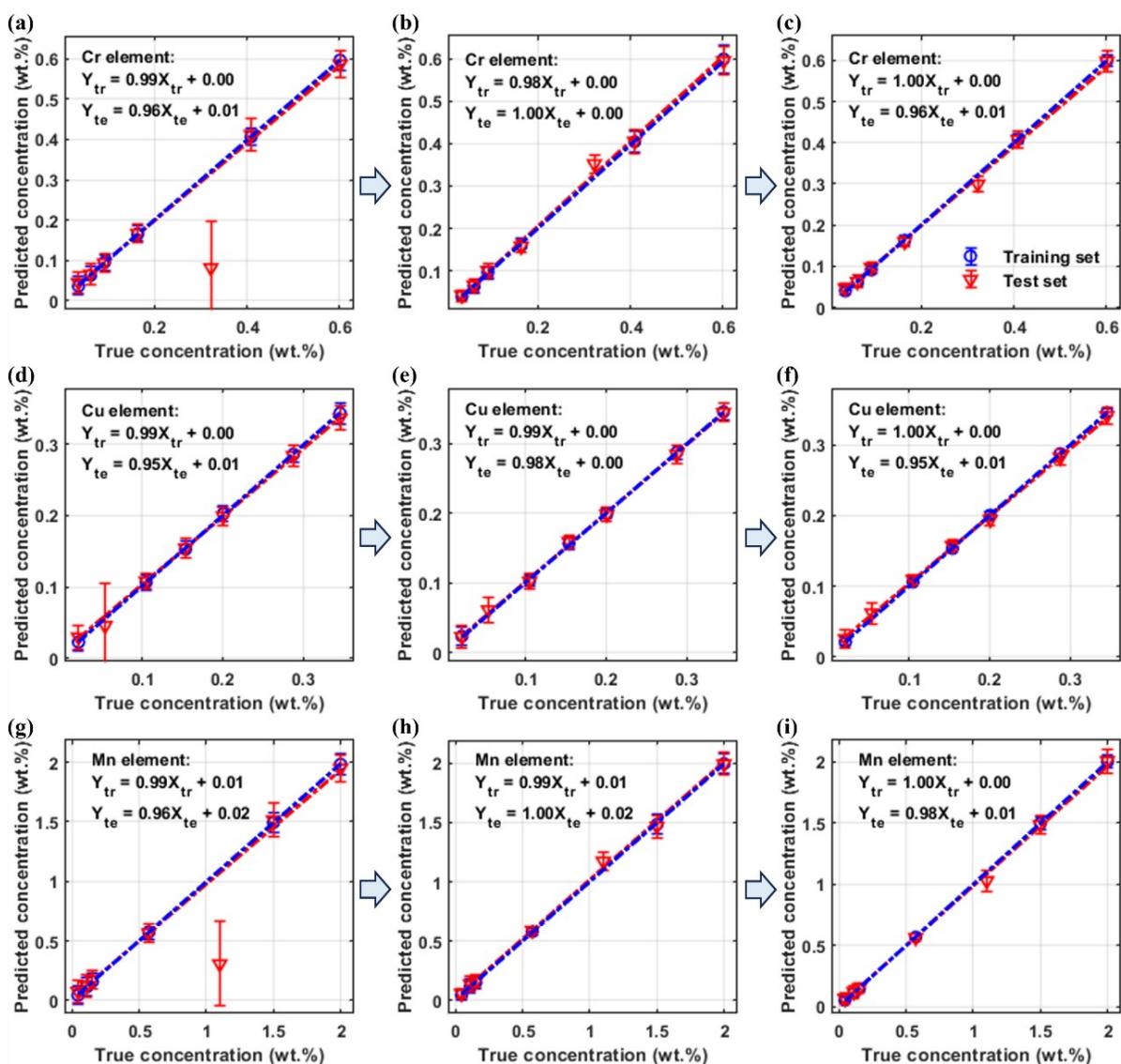


Figure S5. Calibration curves of PLSR models for Cr, Cu, and Mn constructed under the leave-one-concentration-out strategy using (a), (d), (g) acoustic signals, (b), (e), (h) spectra, and (c), (f), (i) feature-level fused data.

Table S1. Evaluation indexes of PLSR regression models for Cr, Cu, and Mn using the leave-one-concentration-out strategy.

Data	Elements	Training set				Test set			
		R ²	RMSE	STD	RSD (%)	R ²	RMSE	STD	RSD (%)
Acoustic signals	Cr	0.9999	0.0218	0.0218	23.2852	0.9799	0.1605	0.0407	42.0661
	Cu	0.9998	0.0120	0.0119	13.8847	0.9997	0.0377	0.0205	31.3621
	Mn	0.9999	0.0765	0.0764	51.5174	0.9779	0.5244	0.1370	56.8982
Spectra	Cr	0.9996	0.0215	0.0202	16.6821	0.9940	0.0287	0.0204	14.2189
	Cu	0.9995	0.0104	0.0101	13.3739	0.9983	0.0154	0.0129	18.2887
	Mn	0.9999	0.0640	0.0607	33.3978	0.9981	0.0842	0.0660	26.5355
Fused data	Cr	0.9998	0.0113	0.0110	10.1856	0.9970	0.0230	0.0171	12.5357

Cu	0.9999	0.0046	0.0046	6.0569	0.9984	0.0136	0.0106	14.1502
Mn	0.9999	0.0400	0.0380	19.3579	0.9986	0.0830	0.0602	22.0324
