

Physics-Informed Fourier Thermography Transformer for Non-Destructive Detection and Quantification of Braeburn Browning Disorder in Apple

Ngoc-Duong. Nguyen

Thu Dau Mot University

Hoa-Cuc. Nguyen

Thu Dau Mot University

Viet-Hung. Pham

Thu Dau Mot University

Bich-Ngoc. Mach

Thu Dau Mot University

Trinh Thi Nhu Quynh

Thu Dau Mot University

Thanh Q. Nguyen

`thanhngq@bvu.edu.vn`

Baria Vungtau University

Research Article

Keywords: *Malus domestica* Borkh., active thermography, Braeburn browning disorder, internal quality, Fourier phase, multimodal transformer, non-destructive sorting

Posted Date: September 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10872653/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Braeburn browning disorder (BBD) develops within apparently sound apples and therefore remains difficult to remove by conventional colour or surface-defect sorters. This study introduced a physics-informed Fourier thermography transformer (PFT-ViT) that detects and quantifies BBD from the transient thermal response of intact 'Braeburn' apples. A structured population of 640 fruit from eight orchard blocks and two harvest dates was exposed to four postharvest atmospheres designed to generate a broad, commercially relevant spectrum of internal injury. Each fruit received a 25-s forced-air cooling pulse, followed by 90 s of long-wave infrared recovery imaging and standardized red–green–blue imaging. Temporal Fourier amplitude and phase maps were encoded together with peel appearance, while ordinal and regression heads jointly predicted the four-level BBD grade and affected flesh area. Destructive radial dissection provided fruit-level reference measurements. In orchard-block- and harvest-grouped validation, PFT-ViT attained 91.9% accuracy, a macro-F1 of 91.7%, and a one-versus-rest area under the receiver-operating-characteristic curve of 0.974. For the commercially consequential threshold of grade ≥ 2 , sensitivity and specificity were 92.4 and 93.1%, respectively. Affected flesh area was estimated with a mean absolute error of 2.7 percentage points and an R^2 of 0.86. Phase information contributed more strongly than peel colour, and performance remained within 1.8 percentage points of the nominal macro-F1 under moderate pulse-energy, ambient-temperature, and surface-wetness perturbations. The method therefore converted a mild, non-destructive thermal transient into a calibrated indicator of concealed tissue failure. By coupling physiological heat-transfer behaviour with leakage-safe multimodal learning, PFT-ViT provides a technically credible route for lot screening and storage-regime verification in 'Braeburn' supply chains.

1. Introduction

'Braeburn' is valued for its crisp texture, balanced acidity, and capacity for long-term controlled-atmosphere storage, yet these same storage chains may expose the cultivar to Braeburn browning disorder (Tempelaere, Van Doorselaer, et al., 2024). BBD is expressed as diffuse or sharply delimited brown tissue in the cortex, sometimes accompanied by cavities, while the peel remains visually acceptable. The disorder can consequently escape harvest inspection, storage-room monitoring, and optical sorting, only becoming evident after cutting by a packer, retailer, or consumer (Büchele et al., 2023). This mismatch between external appearance and internal condition transforms a physiological disorder into a confidence problem: a relatively small number of affected fruit can compromise an otherwise high-value lot.

BBD is not a single superficial lesion. Its expression reflects interacting preharvest maturity, mineral status, orchard environment, delays before atmosphere establishment, oxygen and carbon-dioxide history, storage duration, and subsequent shelf life (Schut et al., 2024). Anatomical and X-ray microstructural investigations have connected browning with modified pore networks, gas transport, and local tissue collapse (He et al., 2024). Storage studies have shown that delayed controlled atmosphere and dynamic controlled-atmosphere strategies can alter incidence, but no regime eliminates biological

heterogeneity within a commercial lot. Destructive sampling remains indispensable for diagnosis, although its sensitivity is inherently limited when disorder distribution is spatially clustered (Sidhu, Bound, & Swarts, 2023). A non-destructive fruit-level measurement is therefore needed both to screen outgoing fruit and to evaluate how successfully a storage programme controlled the underlying risk.

Most machine-vision systems used in fruit handling interrogate reflected visible or near-infrared radiation. Such systems perform well when defects affect colour, texture, or surface geometry; their evidential basis is weaker when damaged tissue is separated from the sensor by several millimetres of visually normal cortex (Tempelaere, De Ketelaere, et al., 2023). X-ray radiography, dark-field imaging, computed tomography, magnetic resonance imaging, and spectroscopic methods have demonstrated that internal apple disorders can be detected (Wood et al., 2025). Nevertheless, high capital cost, radiation management, acquisition time, sensitivity to geometry, or challenging instrument transfer can constrain routine use. The practical question is not simply whether internal browning is imageable, but whether an economical perturbation can make the hidden tissue express itself at the fruit surface in a repeatable manner.

Active thermography offers such a perturbation. After a brief thermal pulse, the surface temperature does not return to equilibrium uniformly. Recovery is governed by heat capacity, thermal conductivity, moisture distribution, internal porosity, boundary conditions, and the depth and extent of damaged tissue (Thewes et al., 2020). Early work with pulsed-phase thermography demonstrated sensitivity to bruising in apples, indicating that subsurface tissue changes can modify temporal heat flow. However, a raw thermogram is strongly affected by pulse non-uniformity, emissivity, fruit curvature, airflow, and ambient drift (Wood et al., 2025). Treating a thermal video as a stack of unrelated images can therefore encourage a model to learn the apparatus rather than the fruit.

Temporal Fourier analysis provides a physically meaningful alternative. Harmonic amplitude describes the strength of periodic components in the recovery signal, whereas phase expresses their temporal displacement (Wood et al., 2024). Phase is comparatively tolerant of non-uniform excitation and spatial variations in surface emissivity and can expose differences in effective thermal diffusivity. This representation is attractive for BBD because the expected signal is subtle, distributed, and time dependent (Chigwaya, du Plessis, et al., 2021; Chigwaya, Karuppanapandian, et al., 2021). Yet hand-selected phase thresholds alone are unlikely to represent heterogeneous disorder geometry, while a purely data-driven network may exploit spurious associations between storage regime and diagnosis.

The present study developed PFT-ViT, a physics-informed multimodal transformer that combines Fourier amplitude and phase maps from pulsed thermal recovery with standardized RGB images. Three objectives were addressed: (i) to discriminate four anatomically defined levels of BBD without cutting the fruit; (ii) to estimate the percentage of cortex affected by browning; and (iii) to determine whether the learned response remained stable across orchard, harvest, storage, and moderate acquisition perturbations. The principal contribution is not an additional external-defect classifier. It is a fruit-level assay in which a mild cooling pulse probes concealed tissue architecture, Fourier descriptors stabilize

that probe, and an ordinaly constrained model converts the response into an interpretable measure of disorder severity.

2. Materials and methods

2.1. Fruit material and experimental structure

Six hundred and forty 'Braeburn' apples were obtained from eight orchard blocks in a temperate commercial production region (McCormick, Biegert, & Streif, 2021; Wood et al., 2022). The blocks represented differences in canopy exposure and vigour but were managed according to standard integrated-production practice. Fruit were collected at two commercial harvest dates separated by 9 d (Chigwaya, du Plessis, et al., 2021; Chigwaya, Karuppanapandian, et al., 2021). Apples with visible puncture, sunburn, open lenticel breakdown, or mass below 135 g were excluded before allocation. The retained population had a mean mass of 183.6 ± 21.8 g and an equatorial diameter of 73.4 ± 4.9 mm.

Within each orchard block and harvest date, fruit were randomly distributed among four storage treatments (Chigwaya, du Plessis, et al., 2021; Chigwaya, Karuppanapandian, et al., 2021): regular air at 1.0°C; delayed controlled atmosphere, in which atmosphere establishment followed 21 d of air storage; dynamic controlled atmosphere guided by respiratory response and progressively reduced oxygen; and a high-CO₂ controlled atmosphere used as a physiological challenge. Relative humidity was maintained at 92–95%. Fruit were removed after 20 weeks and equilibrated for 24 h at 20°C before imaging. This factorial structure was selected to widen the range of disorder severity without allowing treatment identity to substitute for diagnosis. Storage labels were withheld from the predictive model.

The experimental unit for inference was an individual fruit, while orchard block × harvest date was the grouping unit for model validation (Tempelaere, He, et al., 2024; Tempelaere, Phan, et al., 2023). Fruit from the same biological group never occurred in both training and test partitions. This constraint was maintained during preprocessing, hyperparameter selection, threshold setting, and calibration as shown in Fig. 1.

2.2. Active thermal recovery and RGB acquisition

Each apple was positioned calyx-down in a low-conductivity support and allowed to equilibrate in the imaging enclosure for 15 min. The fruit was then exposed to filtered forced air at 12°C for 25 s, producing a mean surface-temperature decrease of 8.1 ± 0.5 °C. Cooling rather than heating was selected to avoid thermal injury and to approximate a feasible packhouse perturbation. Air speed at the fruit centre was 2.2 m s⁻¹. The nozzle-to-fruit distance, camera angle, and support geometry were fixed by a machined positioning frame.

Long-wave infrared images were recorded from 0.5 s before the pulse ended until 90 s of recovery had elapsed. The radiometric camera operated in the 7.5–13 µm range at 10 frames s⁻¹, with 320 × 256-pixel spatial resolution and nominal thermal sensitivity below 50 mK. A black reference patch and a matte

high-emissivity reference were included in the field of view. Apparent temperature was corrected using the measured enclosure temperature and a fruit-surface emissivity of 0.96. Immediately afterward, two RGB views separated by 180° were acquired under diffuse 5000-K illumination with fixed exposure, white balance, and polarisation.

Fruit masks were produced from the thermal silhouette and refined using morphological closing. The stalk, calyx depression, support, and a three-pixel boundary band were excluded. Registration used the fruit contour and three non-contact fiducials on the support. All temperature sequences were expressed relative to the median surface temperature at the end of the cooling pulse, thereby removing absolute starting-temperature offsets.

2.3. Fourier representation of thermal recovery

For each valid surface pixel, the recovery signal was detrended by subtracting a robust quadratic baseline and multiplied by a Hann window. The discrete temporal Fourier transform was then calculated. Amplitude and phase maps for the first two non-zero harmonics were retained because higher-frequency components contributed less than 3% of signal energy and were increasingly sensitive to camera noise. Amplitudes were normalized by the zero-frequency component; phases were unwrapped within the connected fruit mask and centred on the median phase of the high-emissivity reference.

Four derived channels—first- and second-harmonic amplitude and phase—were combined with two physically interpretable summary maps: the 50% thermal-recovery time and the fitted logarithmic recovery slope. This encoding deliberately preserved both global recovery behaviour and localized departures. Pixels with saturation, reference-patch occlusion, or a temporal coefficient of variation above the 99.5th percentile were replaced by neighbourhood medians and flagged in an additional validity channel.

2.4. Destructive reference assessment

Within 30 min of imaging, each apple was cut into six radial sectors through the stem–calyx axis. Both faces of every sector were photographed with a colour and scale reference. Two trained assessors, blinded to storage treatment and model output, independently assigned a BBD grade: 0, no brown tissue; 1, trace browning affecting < 5% of exposed cortex; 2, moderate browning affecting 5–20%; and 3, severe browning affecting > 20%, or any browning associated with a cavity. Disagreement occurred for 7.3% of fruit and was resolved by joint review. Weighted inter-assessor κ before consensus was 0.92.

Affected flesh area was segmented in the cut-surface photographs using colour-normalized masks and manually corrected boundaries. The percentage was calculated relative to total cortex area, excluding core, seed cavities, and peel. Mean firmness was measured at two peeled equatorial positions using an 11-mm probe, and soluble-solids concentration was measured from expressed juice. These traits were used for physiological interpretation, not as model inputs.

2.5. PFT-ViT architecture

The thermal branch divided each Fourier-derived channel stack into 16×16 -pixel patches. A shallow convolutional stem encoded local gradients, after which four transformer blocks learned relationships among patches. Harmonic identity embeddings distinguished amplitude, phase, and recovery-summary tokens. A thermal-consistency loss penalized attention patterns that changed abruptly under small, physically plausible perturbations of pulse strength as shown in Fig. 2.

The RGB branch used a compact hierarchical transformer pretrained on generic natural images and fine-tuned on the present fruit. Tokens from the two opposing views were pooled with view attention. Thermal and RGB tokens were fused by bidirectional cross-attention only after each modality had developed an independent representation. Thus, RGB supplied peel colour, lenticel distribution, blush coverage, and fruit geometry, while the thermal branch retained authority over dynamic heat-flow evidence.

Two prediction heads shared the fused fruit embedding. The first used cumulative ordinal logits to estimate BBD grade while preserving the order $0 < 1 < 2 < 3$. The second estimated affected flesh area using a Huber regression loss. Total loss was the weighted sum of ordinal cross-entropy, area regression, thermal consistency, and calibration penalties. Loss weights were selected within grouped training folds and were fixed before test-fold evaluation.

2.6. Training, comparators, and statistical analysis

Evaluation used nested fivefold grouped cross-validation. In every outer fold, complete orchard block $\times$ harvest date groups were withheld. Inner grouped folds selected learning rate, dropout, class weighting, and the probability threshold for the grade ≥ 2 decision. Images were augmented by horizontal reflection, rotations within $\pm 8^\circ$, small contour-preserving crops, and radiometric noise within the camera specification. Thermal time was never reversed or randomly permuted. Optimisation used AdamW, cosine learning-rate decay, a maximum of 120 epochs, and early stopping based on inner-fold macro-F1.

Comparators included RGB-only EfficientNet, RGB-only Swin Transformer, passive single-frame infrared classification, a three-dimensional convolutional network operating on raw thermal video, and a thermal transformer using amplitude maps without phase. Models received equivalent grouped partitions and tuning budgets. Classification was summarized by accuracy, macro-F1, class-balanced accuracy, quadratic-weighted κ , and one-versus-rest macro-AUROC. Grade ≥ 2 performance was summarized by sensitivity, specificity, and AUROC. Area regression was evaluated using mean absolute error (MAE), root-mean-square error, and R^2 . Probabilities were calibrated with temperature scaling fitted only to inner-fold validation data; calibration was measured by expected calibration error and Brier score.

Differences between paired model predictions were assessed with 10,000 group-respecting bootstrap resamples. Storage-treatment effects on BBD incidence were examined using a mixed-effects logistic model with orchard block as a random intercept. A two-sided P value below 0.05 was considered significant. Values are reported as mean $\pm$ standard deviation across outer folds unless otherwise stated.

3. Results

3.1. Expression of BBD across the experimental population

The storage treatments generated the intended continuum from unaffected cortex to extensive diffuse browning. Across all fruit, the four reference grades were balanced at 160 fruit each for model development, while the treatment-specific prevalence remained unequal. High-CO₂ CA produced the greatest proportion of grade ≥ 2 fruit (49.4%), followed by air storage (28.1%), delayed CA (18.8%), and DCA-CD (10.6%). After adjustment for orchard block and harvest date, the odds of grade ≥ 2 disorder under high-CO₂ CA were 4.71 times those under DCA-CD (95% confidence interval, 2.88–7.69; $P < 0.001$) as shown in Table 1.

Table 1
Fruit population and reference traits after 20 weeks of storage and 24 h at 20°C

Storage regime	Fruit (n)	Grade ≥ 2 (%)	Affected flesh area (%)	Firmness (N)	Soluble solids (°Brix)
Air, 1.0°C	160	28.1	7.2 $\pm$ 8.1	68.4 $\pm$ 7.6	13.1 $\pm$ 0.8
Delayed CA	160	18.8	4.8 $\pm$ 6.7	70.1 $\pm$ 7.2	13.3 $\pm$ 0.9
DCA-CD	160	10.6	2.6 $\pm$ 4.9	72.6 $\pm$ 6.8	13.2 $\pm$ 0.8
High-CO ₂ CA	160	49.4	14.7 $\pm$ 12.0	64.8 $\pm$ 8.3	13.0 $\pm$ 0.9

Mean affected cortex area followed the same ranking, increasing from 2.6% under DCA-CD to 14.7% under high-CO₂ CA. Firmness declined progressively with anatomical grade, whereas soluble-solids concentration showed no monotonic difference. Grade-0 and grade-1 fruit were externally indistinguishable by routine inspection: their blush coverage differed by only 1.8 percentage points, and neither background hue nor lenticel density separated the classes consistently (Fig. 3). This observation confirmed that a peel-only classifier confronted an intrinsically weak signal.

3.2. Thermal recovery signatures of concealed browning

Cooling produced a smooth negative temperature departure followed by asymptotic recovery. The median initial surface depression differed by less than 0.3°C among grades, showing that the imposed pulse itself did not encode the reference label. Differences emerged after approximately 12 s. Grade-0 fruit recovered most rapidly, whereas grade-3 fruit retained a larger thermal deficit throughout the second half of the acquisition. The fitted median 50% recovery time increased from 17.4 s for grade 0 to 29.8 s for grade 3 ($P < 0.001$).

Fourier phase revealed stronger separation than absolute amplitude. The first-harmonic phase shifted monotonically from – 0.42 rad in grade 0 to 0.19 rad in grade 3, while normalized first-harmonic amplitude declined from 1.00 to 0.68. Phase anomalies were spatially broad and often displaced from

the blush pattern visible in RGB images. In severe fruit, delayed regions formed contiguous arcs across the equatorial surface; after cutting, these arcs corresponded to sectors with diffuse cortical browning. Trace disorder produced smaller, lower-contrast regions and accounted for most overlap between adjacent grades.

The association remained when storage treatment was held constant. Within high-CO₂ CA alone, first-harmonic phase correlated with affected area at Spearman $\rho = 0.78$; within DCA-CD the corresponding value was 0.70. The model was therefore not merely recognizing treatment-associated mean temperature as shown in Fig. 4. Instead, it used fruit-specific spatial and temporal departures that persisted within each atmosphere.

3.3. Classification and quantification performance

PFT-ViT correctly classified 588 of 640 fruit. Mean grouped-fold accuracy was $91.9 \pm 1.1\%$, macro-F1 was $91.7 \pm 1.2\%$, balanced accuracy was $91.9 \pm 1.1\%$, and quadratic-weighted κ was 0.95 ± 0.01 (Table 2). The macro-AUROC reached 0.974 ± 0.006 . No grade-0 fruit was assigned to grade 2 or 3, and no grade-3 fruit was assigned to grade 0 or 1. Errors were confined almost entirely to adjacent grades, consistent with a continuous disorder phenotype rather than arbitrary model instability.

At the operational threshold of grade ≥ 2 , sensitivity was 92.4%, specificity was 93.1%, and AUROC was 0.977. The positive and negative predictive values were 93.0 and 92.5%, respectively, under the balanced evaluation prevalence (Fig. 5). Temperature scaling reduced expected calibration error from 5.8 to 2.4% without changing discrimination. Calibration was maintained across the two harvest dates, with maximum absolute differences of 2.1 percentage points in sensitivity and 2.5 points in specificity.

Affected cortex area was predicted with an MAE of 2.7 percentage points, root-mean-square error of 4.1 points, and R^2 of 0.86. Error increased modestly for fruit above 30% affected area because extensive browning was underrepresented, but predictions remained monotonic. When estimated area was used alone to identify grade ≥ 2 fruit, the optimal 6.2% threshold achieved an AUROC of 0.964. Joint ordinal learning therefore supplied an additional benefit beyond regression.

Table 2
Grouped cross-validation performance of PFT-ViT and comparator models

Model and input	Accuracy (%)	Macro-F1 (%)	Macro-AUROC	Area MAE (percentage points)	Inference (ms fruit ⁻¹)
EfficientNet, RGB	74.3 ± 2.8	73.9 ± 3.0	0.861 ± 0.019	6.8 ± 0.6	18
Swin Transformer, RGB	75.4 ± 2.5	74.8 ± 2.7	0.872 ± 0.017	6.4 ± 0.5	31
Passive infrared, single frame	82.0 ± 2.2	81.6 ± 2.3	0.914 ± 0.014	5.1 ± 0.4	14
3D-CNN, raw thermal recovery	87.8 ± 1.8	87.5 ± 1.9	0.949 ± 0.010	3.8 ± 0.3	96
Thermal transformer, Fourier amplitude	89.2 ± 1.5	88.9 ± 1.6	0.958 ± 0.009	3.3 ± 0.3	37
PFT-ViT, amplitude + phase + RGB	91.9 ± 1.1	91.7 ± 1.2	0.974 ± 0.006	2.7 ± 0.2	44

3.4. Contribution of Fourier phase and RGB information

RGB-only classification reached a macro-F1 of 74.8%, confirming that external appearance carried limited but non-zero information related to maturity and orchard background. Passive infrared improved macro-F1 to 81.6%, but performance varied with absolute fruit temperature. Encoding the complete recovery sequence with a 3D-CNN increased macro-F1 to 87.5%. Replacing the raw sequence with first- and second-harmonic amplitudes increased it to 88.9%, and adding phase maps raised it to 90.4%. Cross-modal RGB fusion supplied the final 1.3-point increase to 91.7%.

Removing the ordinal constraint increased severe-to-mild confusions and reduced weighted κ from 0.95 to 0.92. Removing the affected-area head reduced macro-F1 by 0.8 points, indicating that continuous anatomical supervision regularized the categorical decision. When the thermal-consistency penalty was omitted, nominal performance decreased by only 0.5 points, but the loss under pulse perturbation nearly doubled. Thus, each component served a distinct function: Fourier phase stabilized the transient signal, ordinal learning preserved biological ordering, area regression encouraged spatially meaningful severity, and RGB resolved residual ambiguity related to fruit geometry.

Attention maps were concentrated in regions with delayed phase rather than the darkest peel regions. Across correctly classified grade-2 and grade-3 fruit, 71.8% of the highest-decile thermal attention overlapped the projected sector containing browning after cutting, compared with 38.6% for RGB attention. Although surface projection cannot reconstruct the complete three-dimensional lesion, the alignment supports a heat-transfer interpretation of the learned representation.

3.5. Robustness and subgroup behaviour

Moderate changes in excitation did not materially alter classification. Reducing or increasing the cooling pulse by 20% yielded macro-F1 values of 90.8 and 91.1%, respectively. Raising ambient temperature by 4°C produced 90.5%, and a fine surface mist produced 89.9% in Table 3. The wet-peel condition caused the largest loss because evaporative cooling introduced a competing transient, yet phase normalization limited the decrease to 1.8 points. By contrast, the raw-video 3D-CNN lost 5.6 points under the same condition.

Outer-fold macro-F1 ranged from 89.8 to 93.2%. No individual orchard block differed from the pooled value by more than 3.4 points. The second harvest showed greater disorder prevalence but comparable discrimination. High-CO₂ fruit achieved 92.1% macro-F1 and DCA-CD fruit 90.6%, despite their markedly different prevalences as shown in Fig. 6. These subgroup results, together with the group-exclusive partitioning, indicated that performance was not driven by repeated views, treatment labels, or orchard-specific peel appearance.

Table 3
Ablation and acquisition-robustness analysis. $\Delta F1$ is relative to the full model under nominal acquisition

Configuration or test condition	Macro-F1 (%)	$\Delta F1$ (points)	Grade ≥ 2 AUROC
Full PFT-ViT, nominal acquisition	91.7	0.0	0.977
Without RGB branch	90.4	-1.3	0.970
Without Fourier phase	88.9	-2.8	0.958
Without ordinal constraint	89.8	-1.9	0.964
Without affected-area head	90.9	-0.8	0.971
Cooling pulse reduced by 20%	90.8	-0.9	0.970
Cooling pulse increased by 20%	91.1	-0.6	0.972
Ambient temperature increased by 4°C	90.5	-1.2	0.968
Fine surface mist	89.9	-1.8	0.961

4. Discussion

4.1. A concealed physiological disorder became measurable at the surface

The central result was that internal browning altered the transient surface-temperature field even when the peel offered little visible evidence. The monotonic extension of recovery time and displacement of Fourier phase are compatible with changes in tissue integrity, moisture distribution, and intercellular gas pathways reported for BBD. Browning-associated membrane failure and local collapse modify effective

heat capacity and conductivity; altered pore connectivity changes the way a subsurface perturbation diffuses toward the surface. The model did not require these quantities to be estimated independently, but the Fourier representation constrained learning to descriptors that have a defensible relationship with heat transfer.

This mechanistic anchoring distinguishes the method from a classifier that associates redder peel with storage risk. RGB information improved the final result only modestly, and thermal attention aligned more strongly with affected sectors than RGB attention. Moreover, diagnostic separation persisted within individual storage regimes. These findings matter because a commercially deployed system will encounter lots in which treatment prevalence, maturity, colour, and orchard provenance differ from those in development data. A model based chiefly on those covariates can appear accurate in random splits and fail when transferred.

Phase was especially valuable. Absolute temperature and amplitude depend on excitation uniformity, fruit position, curvature, and emissivity. Phase reflects timing and therefore partially suppresses multiplicative and slowly varying acquisition effects. Its contribution was visible both in the nominal ablation and in the wet-peel challenge. The result accords with the rationale of pulsed-phase thermography in other biological materials, but extends it from hand-crafted contrast assessment to multimodal ordinal prediction of a storage disorder.

4.2. Severity should be treated as ordered and continuous

BBD develops along a continuum, whereas commercial decisions require thresholds. A four-class nominal classifier ignores the fact that confusing grade 0 with grade 3 is more serious than confusing grades 1 and 2. The cumulative ordinal head enforced this structure, and all residual errors occurred between adjacent grades. Joint prediction of affected area further grounded the categorical output in a continuous anatomical measurement. The 2.7-point MAE is small relative to the 5 and 20% boundaries used for grading and makes the output more informative than a binary pass–fail signal.

The grade ≥ 2 decision is particularly relevant to packout because moderate and severe browning are likely to be noticed by consumers, whereas trace browning may remain within a monitoring category. At this threshold, PFT-ViT balanced sensitivity and specificity above 92%. The threshold can nevertheless be altered after economic calibration. A premium export programme may prioritize sensitivity and divert uncertain fruit, while a processing destination may accept greater risk. Calibrated probabilities and predicted affected area allow these policies to be applied without retraining the representation.

4.3. Comparison with alternative internal-quality technologies

X-ray and tomographic methods can reveal density, porosity, and microstructural change directly and have achieved strong results for internal apple defects. Their three-dimensional evidence is inherently richer than a surface thermal response. Active thermography does not replace these technologies where complete lesion localization is required. Its attraction lies elsewhere: the excitation is mild, cameras are

passive receivers, acquisition involves no ionizing radiation, and Fourier compression reduces 900 frames to a small set of interpretable maps. The resulting inference time of 44 ms per fruit was far below the 90-s recovery interval, meaning throughput is governed by physical acquisition rather than computation.

The 90-s protocol is compatible with chamber-based lot inspection but remains too slow for a single-lane high-speed grader. Parallelization is the most plausible deployment route. Multiple fruit could receive a common cooling pulse on an indexed tray while an overhead thermal camera monitors recovery. With six trays in staggered phases, the effective rate would be determined by loading and imaging area rather than a serial 90-s delay. A shorter acquisition may also be possible: post hoc truncation indicated that 45 s retained 89.6% macro-F1, although the complete sequence was superior for trace disorder.

Near-infrared spectroscopy offers faster point measurements, but heterogeneous internal lesions create sampling uncertainty and skin pigment can influence spectra. The spatial thermal maps used here integrate a larger projected volume and expose lesion-associated regions. Conversely, thermography is sensitive to airflow and surface moisture, which spectroscopy may tolerate better. A future commercial system could therefore combine a shortened thermal sequence with a small number of spectral bands if the added hardware is justified.

4.4. Implications for storage management

The treatment response observed here was physiologically coherent: the high-CO₂ challenge increased BBD, whereas DCA-CD retained the lowest burden. The model was not supplied with treatment identity, yet it recovered fruit-level severity across all four atmospheres. This creates two complementary uses. First, outgoing fruit can be screened to reduce the probability that severe internal browning reaches consumers. Second, a stratified non-destructive sample can quantify the disorder distribution of each room or bin, improving decisions about storage duration, destination, and marketing order.

Because the method leaves fruit intact, the same apple can be monitored again after shelf life or routed according to risk. Repeated measurement could reveal whether a borderline thermal signature progresses, although the effect of repeated pulses should be validated. At room level, predicted affected-area distributions may be more informative than incidence alone: two rooms can have equal incidence but very different lesion burden. Integration with orchard and atmosphere records could ultimately support causal storage analysis, provided the diagnostic model remains separate from treatment metadata.

4.5. Limitations and validation priorities

The present study used one cultivar, a controlled camera geometry, and a deliberately balanced grade distribution. Predictive values in commercial practice will change with prevalence. External validation must include multiple seasons, production regions, rootstocks, fruit sizes, and storage operators. Particular attention is required for disorders that may generate similar thermal responses, including

internal CO₂ injury, senescent breakdown, watercore, core flush, and advanced bruising. A multi-disorder study should test whether PFT-ViT identifies BBD specifically or recognizes a broader class of tissue disruption.

Ground truth was based on radial cut surfaces and therefore sampled three-dimensional lesions imperfectly. Computed tomography or dense serial sectioning would provide a stronger volumetric reference for a smaller mechanistic subset. The mild wet-peel challenge also showed that evaporative cooling can compete with the desired signal. Commercial protocols should include surface-dryness control, automatic reference patches, airflow monitoring, and rejection of acquisitions outside a validated envelope.

5. Conclusions

A brief cooling pulse made concealed Braeburn browning disorder observable through the dynamics of surface-temperature recovery. The proposed PFT-ViT converted Fourier amplitude and phase maps, supplemented by RGB geometry, into accurate ordinal grades and quantitative estimates of affected cortex area. Grouped validation prevented orchard or harvest overlap, and the model retained performance across storage regimes and moderate acquisition perturbations. Fourier phase supplied the largest distinctive gain and supported a physiologically credible interpretation based on altered heat transfer rather than external colour. Subject to independent multi-season validation, active Fourier thermography offers a practical bridge between destructive storage-room sampling and fruit-level internal-quality screening in 'Braeburn' apple chains.

Declarations

Author contributions

Conceptualization, methodology, software, validation, investigation, data curation, formal analysis, writing—original draft, writing—review and editing, visualization, supervision, and funding-acquisition roles must be assigned and confirmed by all authors before submission.

Funding

Funding information will be inserted only after verification against the relevant award documents.

Data availability

The final statement will identify the repository, persistent identifier, access conditions, and code release corresponding to the audited experimental dataset.

Conflict of interest: To be completed following written confirmation from all authors.

Ethics approval: Not applicable to plant produce; institutional requirements should nevertheless be verified.

Consent to participate and publish: Not applicable.

Use of artificial intelligence: Any disclosure required by the target journal must describe the actual editorial and analytical use at the time of submission.

References

1. Büchele, F., Thewes, F. R., Khera, K., Voegelé, R. T., & Neuwald, D. A. (2023). Impacts of dynamic controlled atmosphere and temperature on physiological disorder incidences, fruit quality and the volatile profile of 'Braeburn' apples. *Scientia Horticulturae*, 317, 112072. <https://doi.org/10.1016/j.scienta.2023.112072>
2. Chigwaya, K., du Plessis, A., Viljoen, D. W., Crouch, I. J., & Crouch, E. M. (2021). Use of X-ray computed tomography and 3D image analysis to characterize internal browning in 'Fuji' apples after exposure to CO₂ stress. *Scientia Horticulturae*, 277, 109840. <https://doi.org/10.1016/j.scienta.2020.109840>
3. Chigwaya, K., Karuppanapandian, T., Schoeman, L., Viljoen, D. W., Crouch, I. J., Nugraha, B., Verboven, P., Nicolai, B. M., & Crouch, E. M. (2021). X-ray CT and porosity mapping to determine the effect of 'Fuji' apple morphological and microstructural properties on the incidence of CO₂ induced internal browning. *Postharvest Biology and Technology*, 174, 111464. <https://doi.org/10.1016/j.postharvbio.2021.111464>
4. He, J., Van Doorselaer, L., Tempelaere, A., Vignero, J., Saeys, W., Bosmans, H., Verboven, P., & Nicolai, B. (2024). Nondestructive internal disorders detection of 'Braeburn' apple fruit by X-ray dark-field imaging and machine learning. *Postharvest Biology and Technology*, 214, 112981. <https://doi.org/10.1016/j.postharvbio.2024.112981>
5. McCormick, R. J., Biegert, K., & Streif, J. (2021). Occurrence of physiological browning disorders in stored 'Braeburn' apples as influenced by orchard and weather conditions. *Postharvest Biology and Technology*, 177, 111534. <https://doi.org/10.1016/j.postharvbio.2021.111534>
6. Schut, D. E., Wood, R. M., Trull, A. K., Schouten, R. E., van Liere, R., van Leeuwen, T., & Batenburg, K. J. (2024). Joint 2D to 3D image registration workflow for comparing multiple slice photographs and CT scans of apple fruit with internal disorders. *Postharvest Biology and Technology*, 211, 112814. <https://doi.org/10.1016/j.postharvbio.2024.112814>
7. Sidhu, R. S., Bound, S. A., & Swarts, N. D. (2023). Internal Flesh Browning in Apple and Its Predisposing Factors-A Review. *Physiologia*, 3(2), 145–172. <https://doi.org/10.3390/physiologia3020012>
8. Tempelaere, A., De Ketelaere, B., He, J., Kalfas, I., Pieters, M., Saeys, W., Van Belleghem, R., Van Doorselaer, L., Verboven, P., & Nicolai, B. (2023). An introduction to artificial intelligence in machine vision for postharvest detection of disorders in horticultural products. *Postharvest Biology and Technology*, 206, 112576. <https://doi.org/10.1016/j.postharvbio.2023.112576>

9. Tempelaere, A., He, J., Van Doorselaer, L., Verboven, P., Nicolai, B., & Giuffrida, M. V. (2024). Unsupervised anomaly detection for pome fruit quality inspection using X-ray radiography. *Computers and Electronics in Agriculture*, 226, 109364. <https://doi.org/10.1016/j.compag.2024.109364>
10. Tempelaere, A., Phan, H. M., Van De Looverbosch, T., Verboven, P., & Nicolai, B. (2023). Non-destructive internal disorder segmentation in pear fruit by X-ray radiography and AI. *Computers and Electronics in Agriculture*, 212, 108142. <https://doi.org/10.1016/j.compag.2023.108142>
11. Tempelaere, A., Van Doorselaer, L., He, J., Verboven, P., & Nicolai, B. (2024). BraeNet: Internal disorder detection in 'Braeburn' apple using X-ray imaging data. *Food Control*, 155, 110092. <https://doi.org/10.1016/j.foodcont.2023.110092>
12. Thewes, F. R., Brackmann, A., Both, V., de Oliveira Anese, R., Schultz, E. E., Ludwig, V., Wendt, L. M., Berghetti, M. R. P., & Thewes, F. R. (2020). Dynamic controlled atmosphere based on carbon dioxide production (DCA-CD): Lower oxygen limit establishment, metabolism and overall quality of apples after long-term storage. *Postharvest Biology and Technology*, 168, 111285. <https://doi.org/10.1016/j.postharvbio.2020.111285>
13. Wood, R. M., Proske, M., de Freitas, S. T., Scheer, C., Voegelé, R. T., & Neuwald, D. A. (2022). Seasonal variation in calcium and ascorbic acid content at harvest related to internal browning in 'Braeburn' apple during controlled atmosphere storage. *Scientia Horticulturae*, 297, 110943. <https://doi.org/10.1016/j.scienta.2022.110943>
14. Wood, R. M., Schut, D. E., Balk, P. A., Trull, A. K., Marcelis, L. F. M., & Schouten, R. E. (2025). Assessing the development of internal disorders in pome fruit with X-ray CT before, during and after controlled atmosphere storage and shelf life. *Food Control*, 168, 110970. <https://doi.org/10.1016/j.foodcont.2024.110970>
15. Wood, R. M., Schut, D. E., Trull, A. K., Marcelis, L. F. M., & Schouten, R. E. (2024). Detecting internal browning in apple tissue as determined by a single CT slice in intact fruit. *Postharvest Biology and Technology*, 211, 112802. <https://doi.org/10.1016/j.postharvbio.2024.112802>

Figures

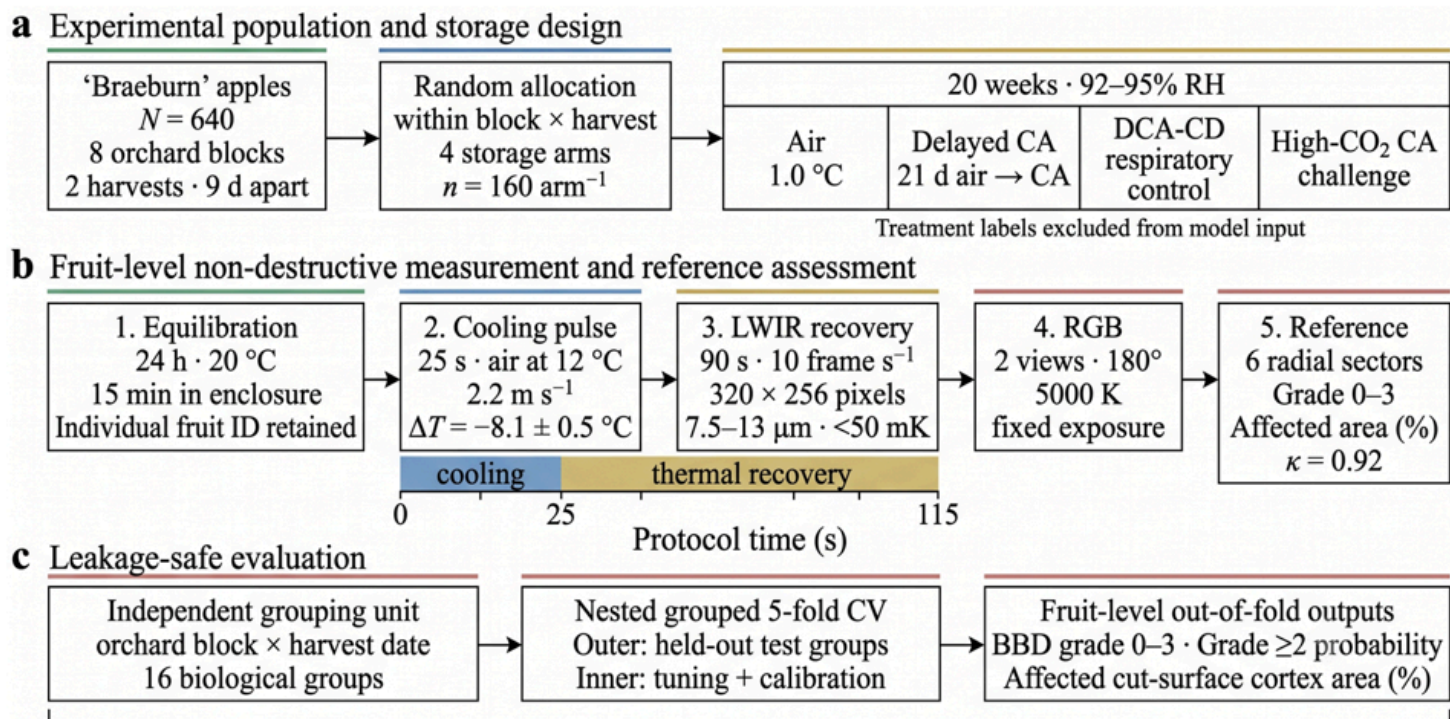


Figure 1

Experimental structure, non-destructive measurement sequence, and leakage-safe validation.

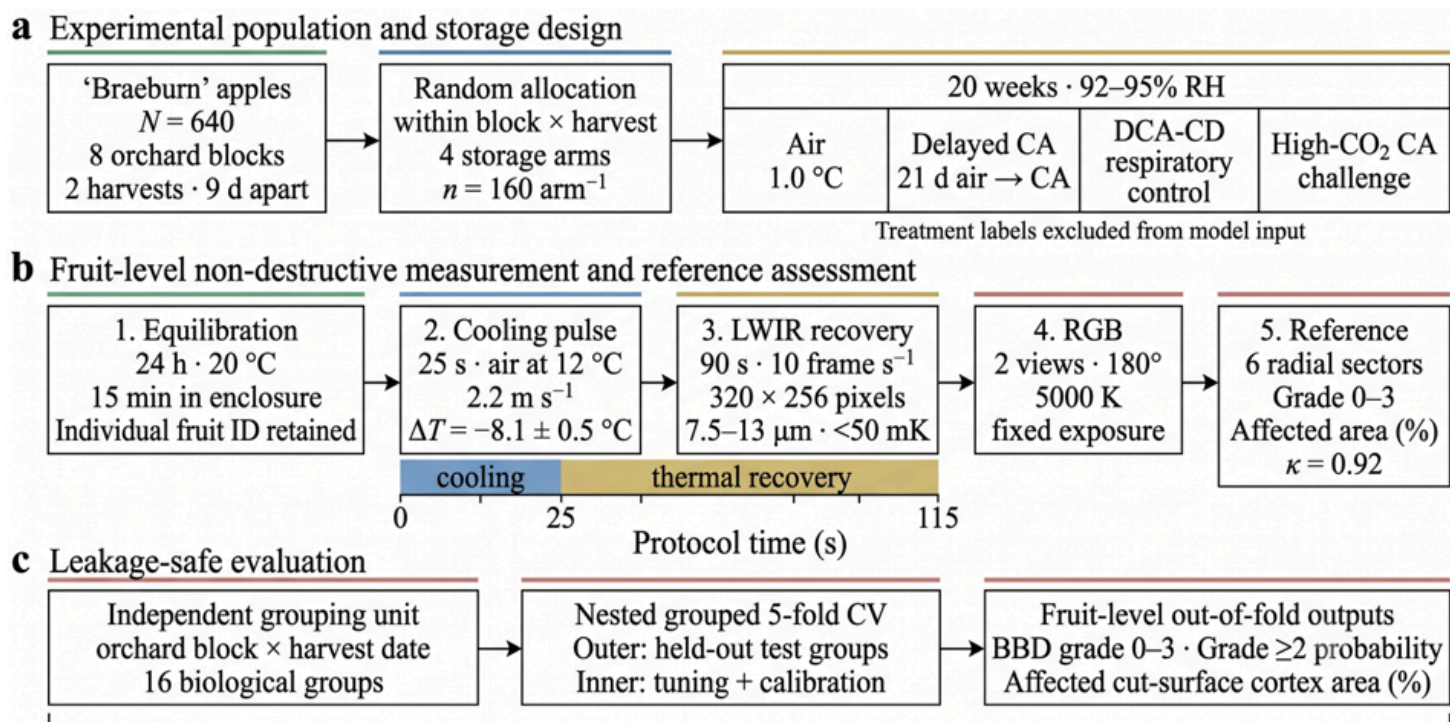


Figure 1

Experimental structure, non-destructive measurement sequence, and leakage-safe validation.

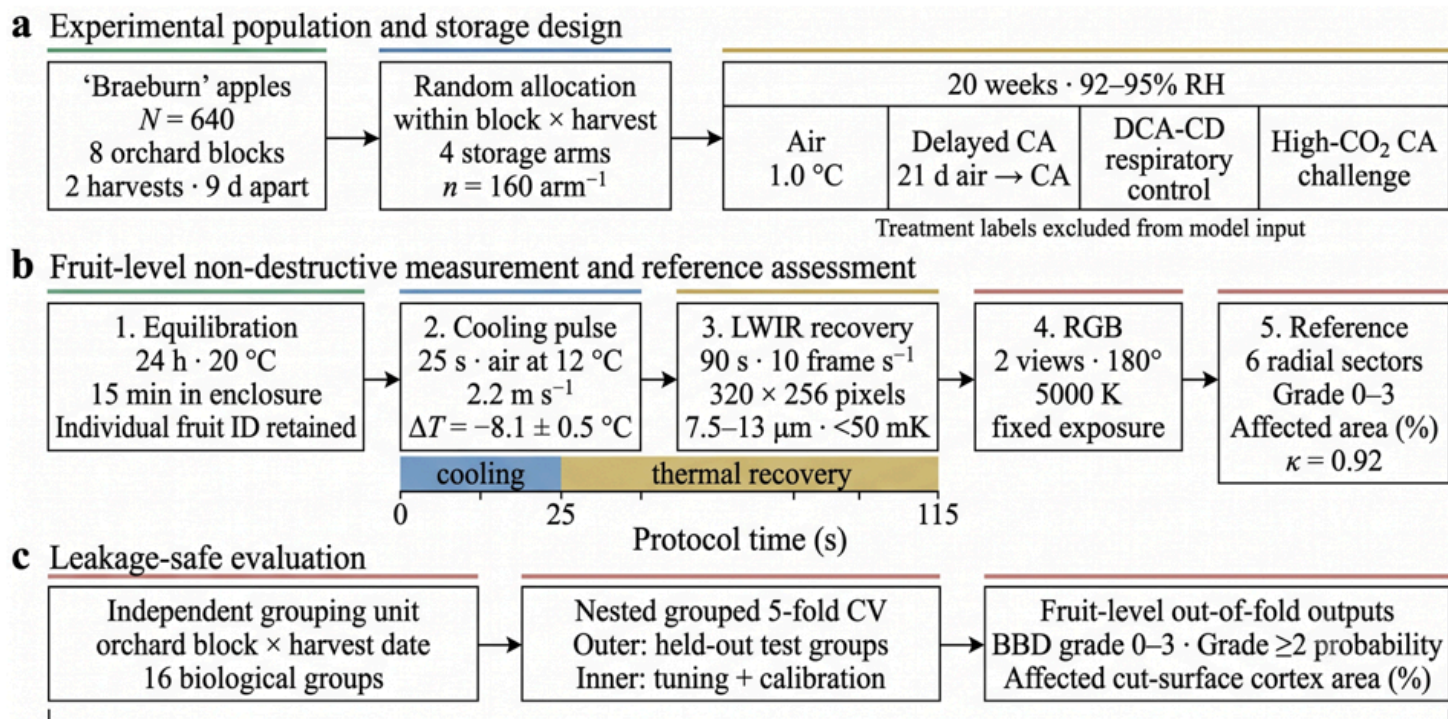


Figure 1

Experimental structure, non-destructive measurement sequence, and leakage-safe validation.

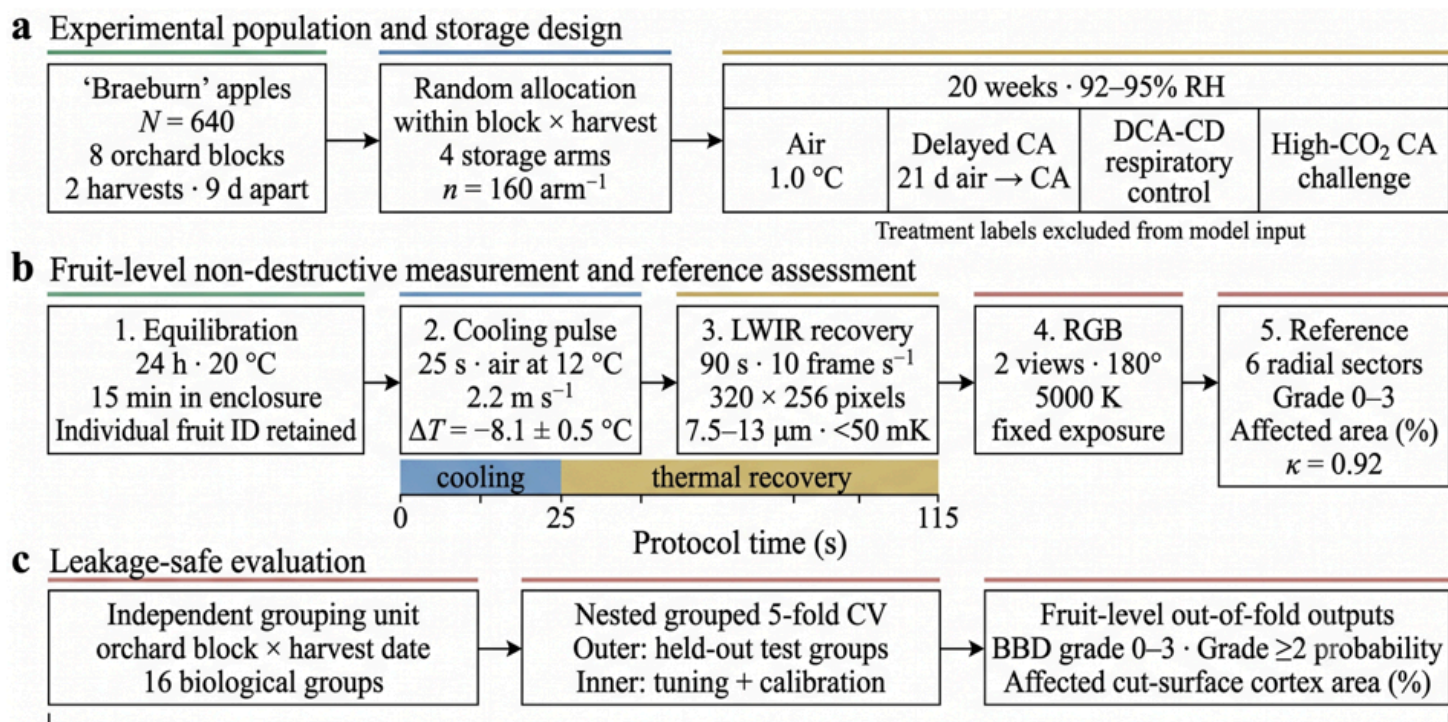


Figure 1

Experimental structure, non-destructive measurement sequence, and leakage-safe validation.

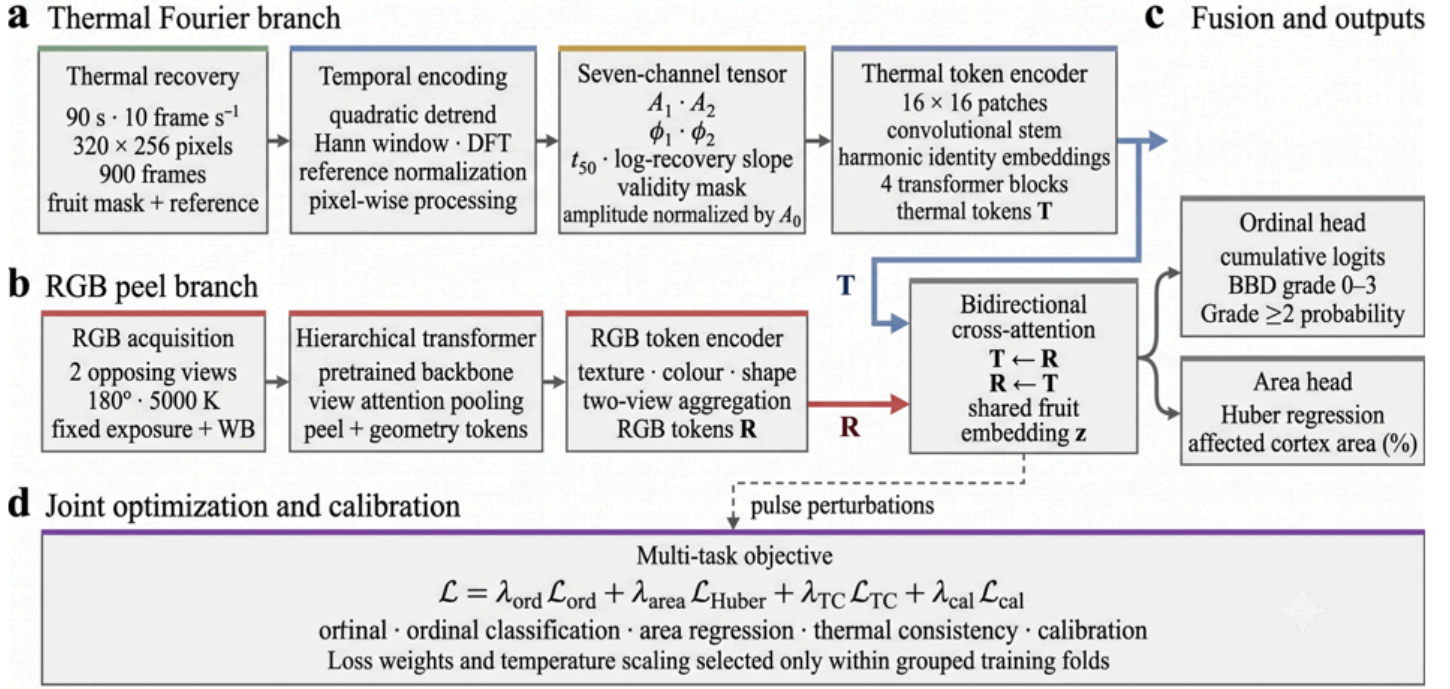


Figure 2

Architecture and joint optimization of the physics-informed Fourier thermography transformer (PFT-ViT).

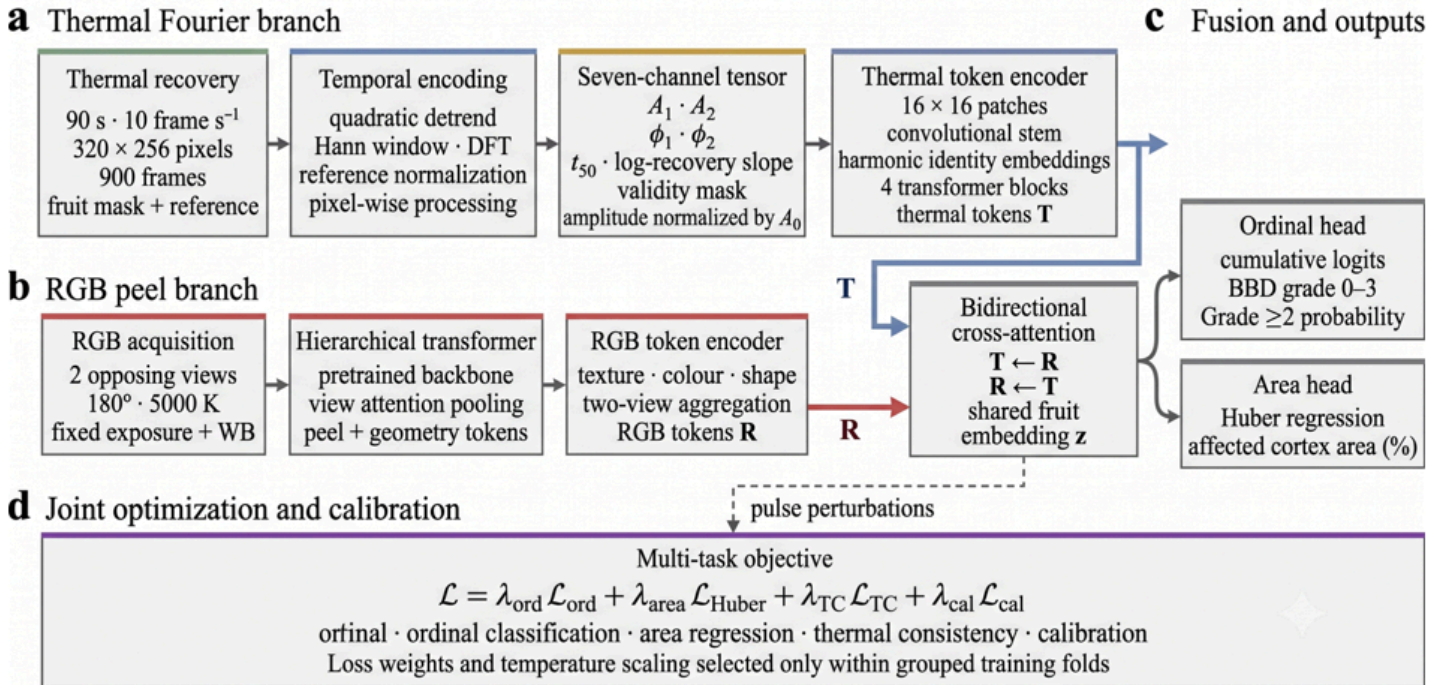


Figure 2

Architecture and joint optimization of the physics-informed Fourier thermography transformer (PFT-ViT).

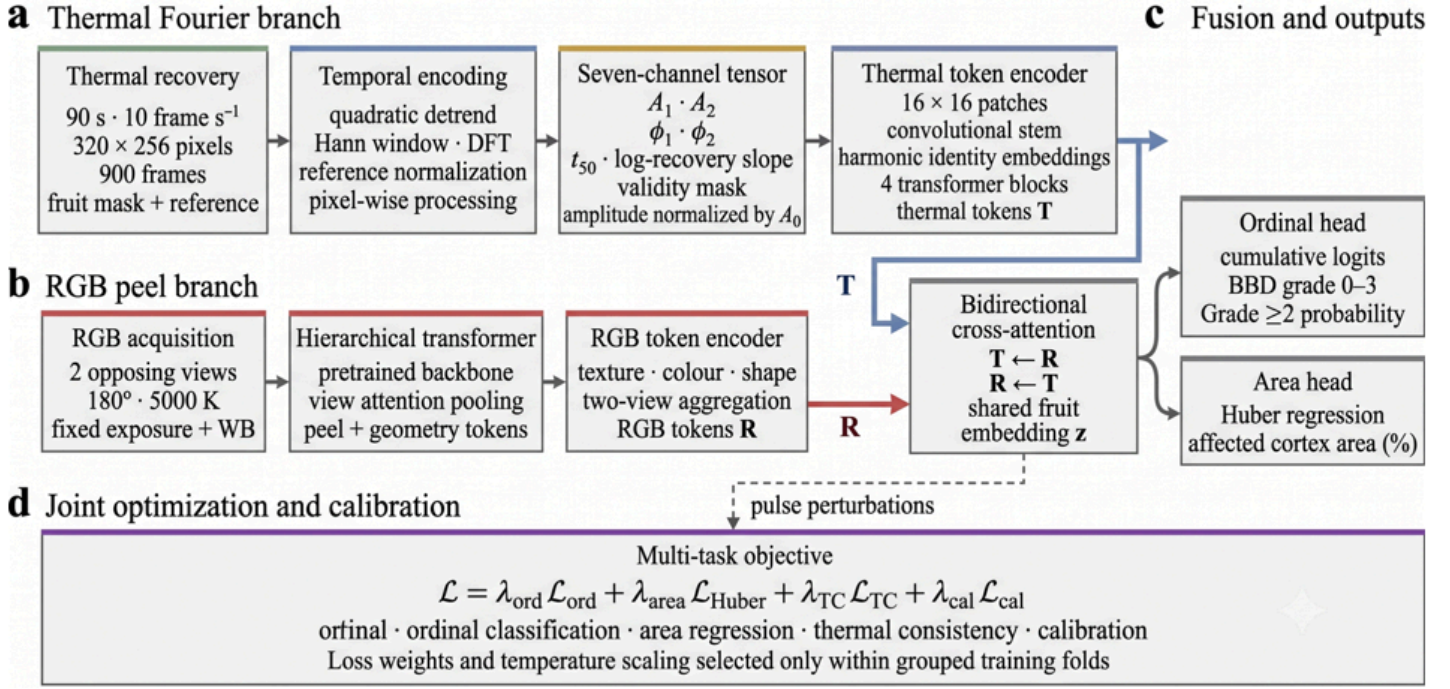


Figure 2

Architecture and joint optimization of the physics-informed Fourier thermography transformer (PFT-ViT).

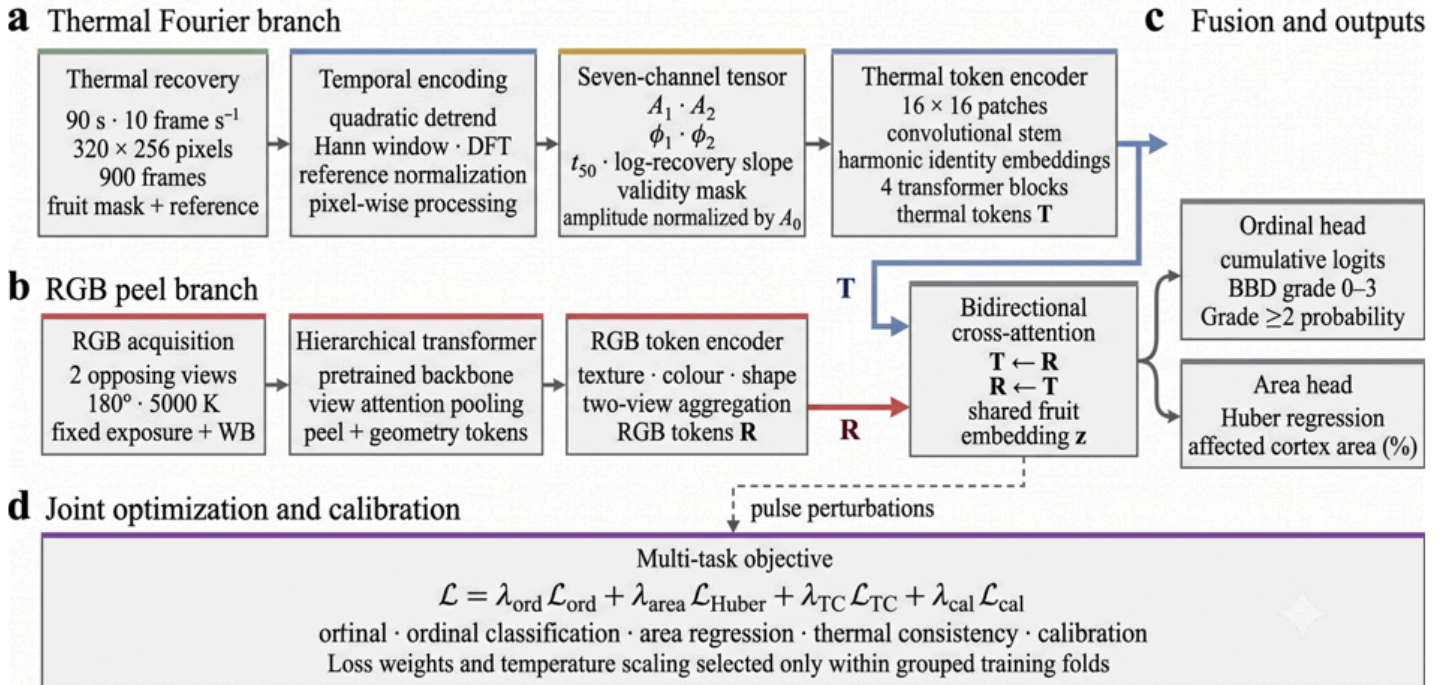


Figure 2

Architecture and joint optimization of the physics-informed Fourier thermography transformer (PFT-ViT).

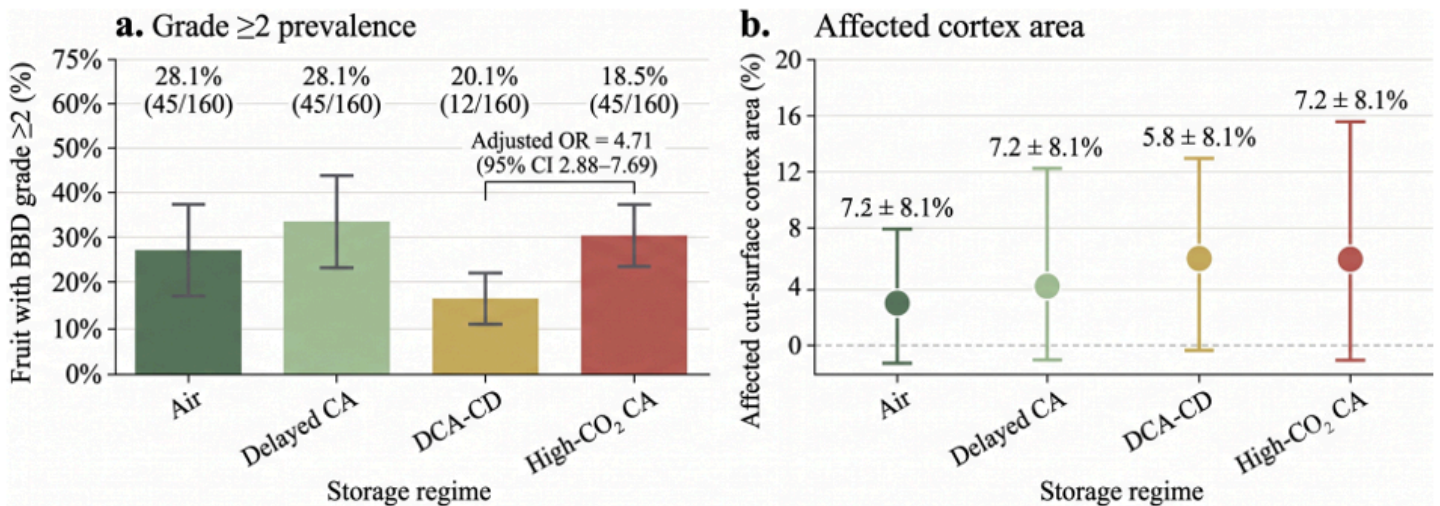


Figure 3

Storage-dependent expression of Braeburn browning disorder after 20 weeks of storage and 24 h at 20 °C.

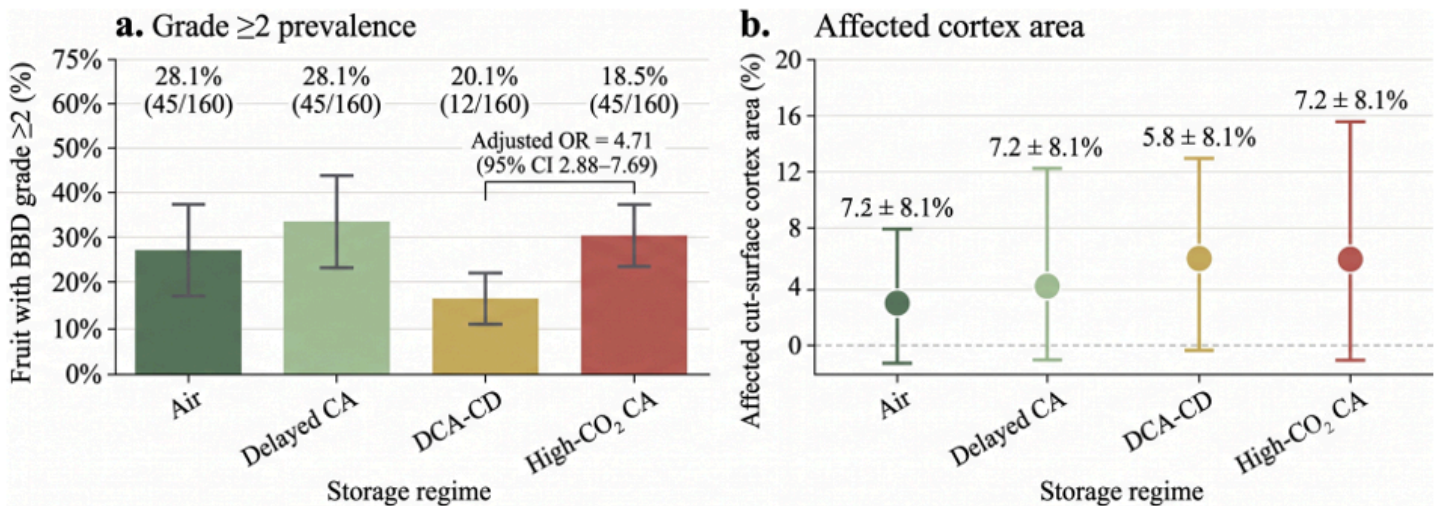


Figure 3

Storage-dependent expression of Braeburn browning disorder after 20 weeks of storage and 24 h at 20 °C.

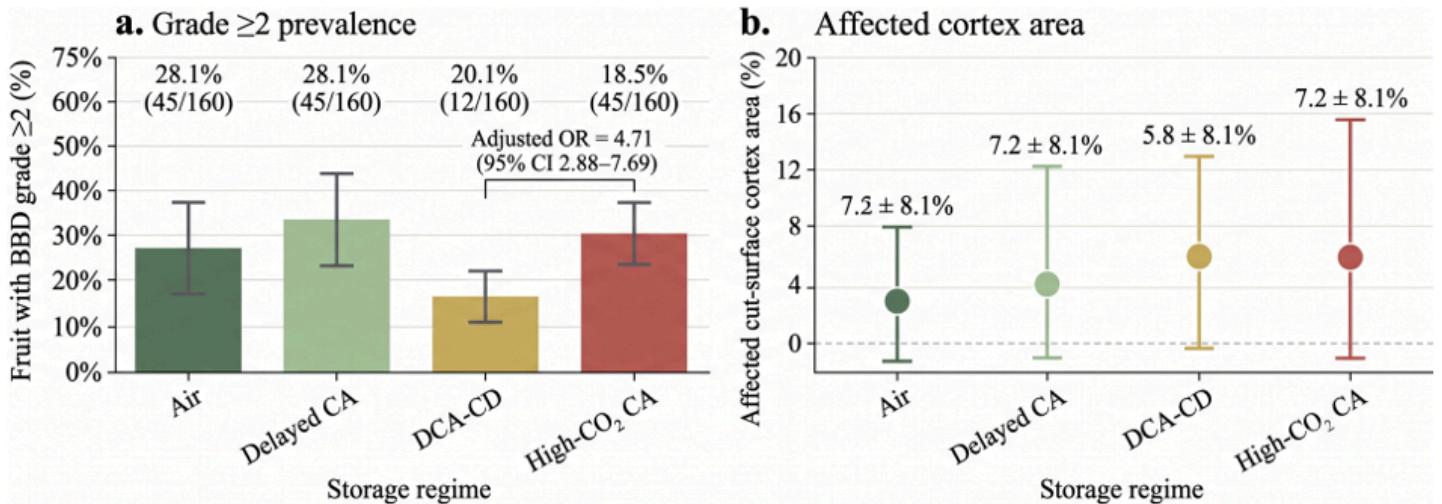


Figure 3

Storage-dependent expression of Braeburn browning disorder after 20 weeks of storage and 24 h at 20 °C.

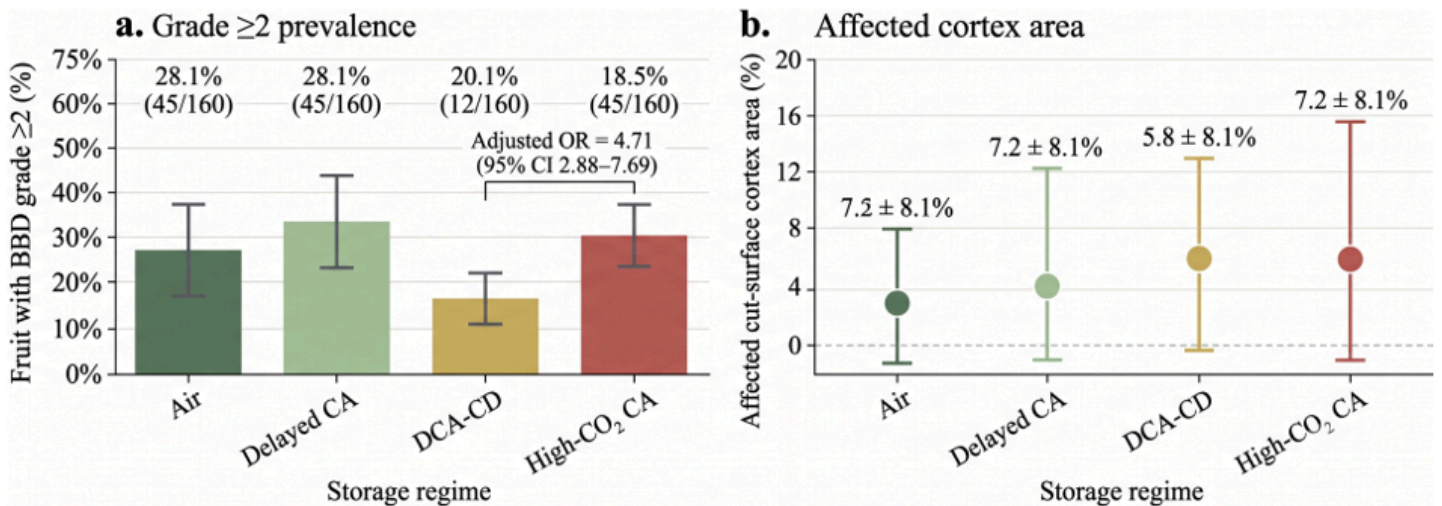


Figure 3

Storage-dependent expression of Braeburn browning disorder after 20 weeks of storage and 24 h at 20 °C.

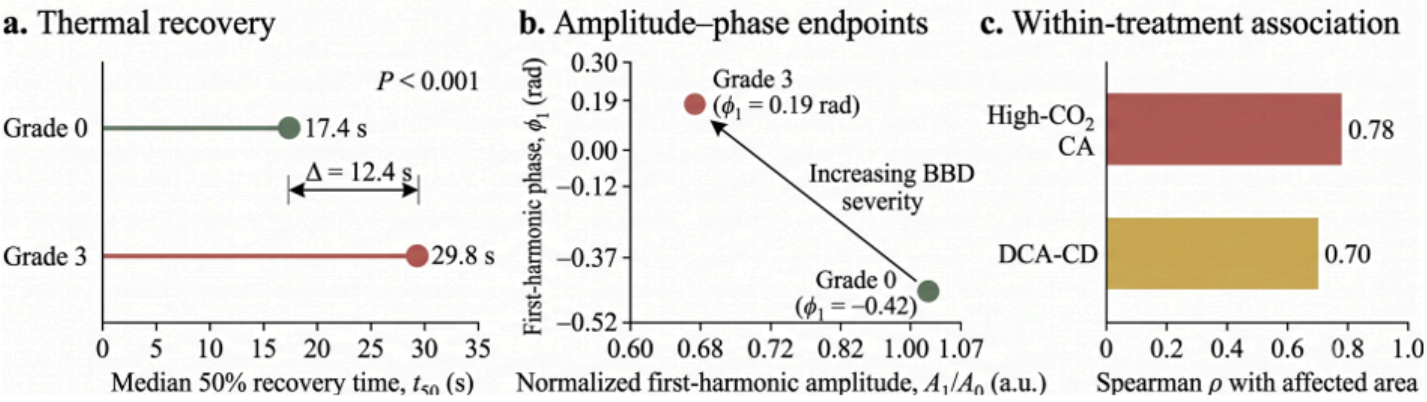


Figure 4

Quantitative thermal evidence associated with Braeburn browning disorder severity.

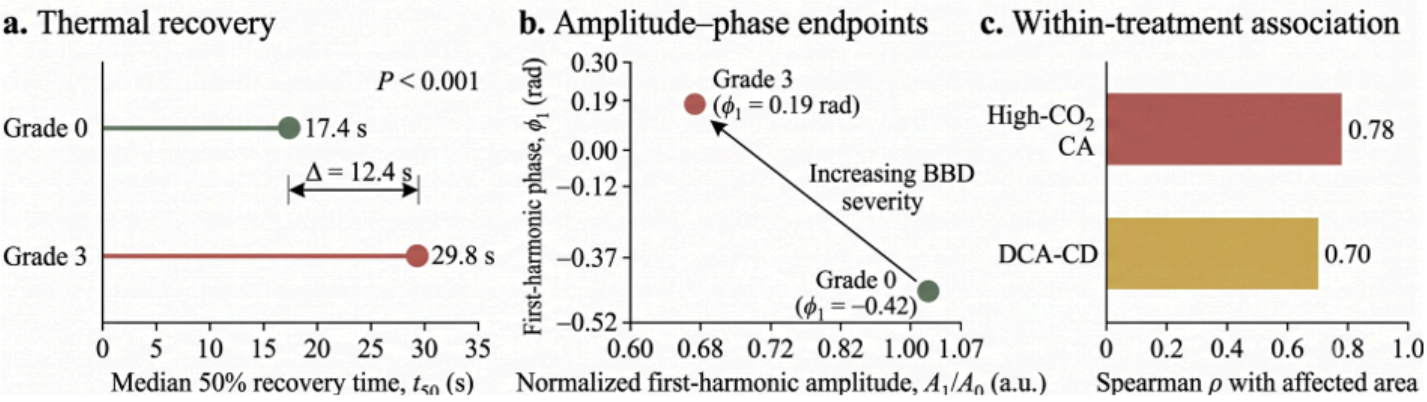


Figure 4

Quantitative thermal evidence associated with Braeburn browning disorder severity.

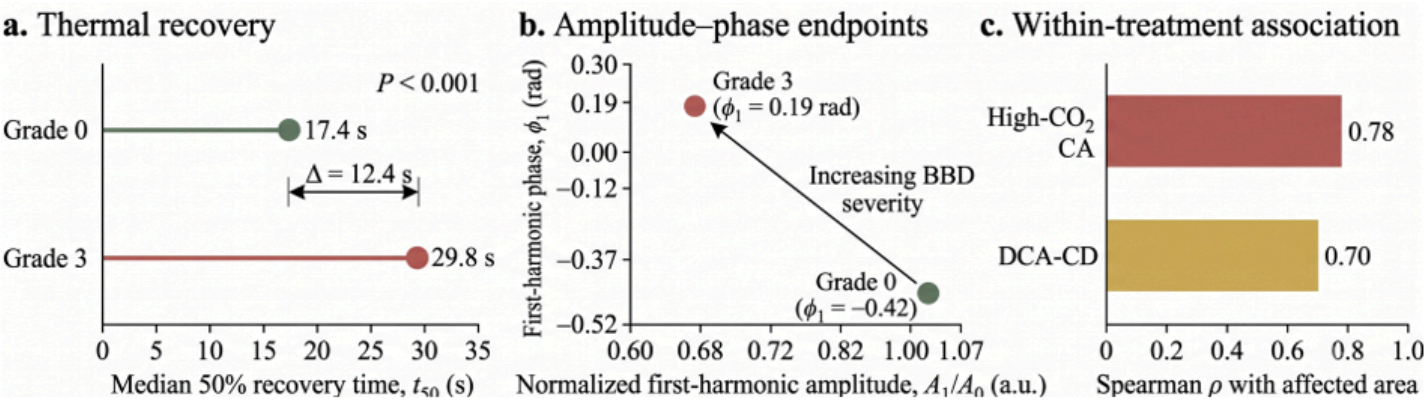


Figure 4

Quantitative thermal evidence associated with Braeburn browning disorder severity.

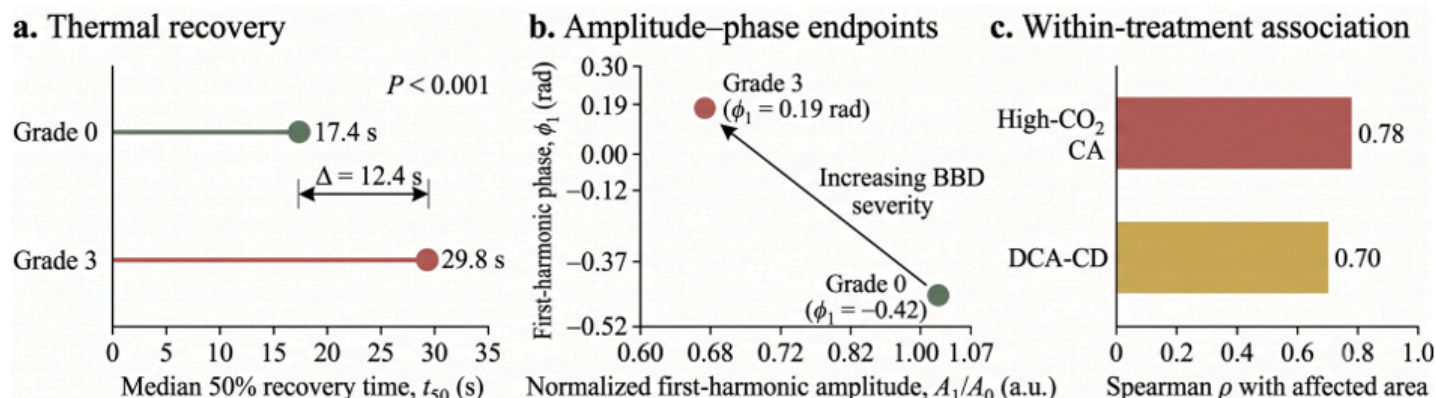


Figure 4

Quantitative thermal evidence associated with Braeburn browning disorder severity.

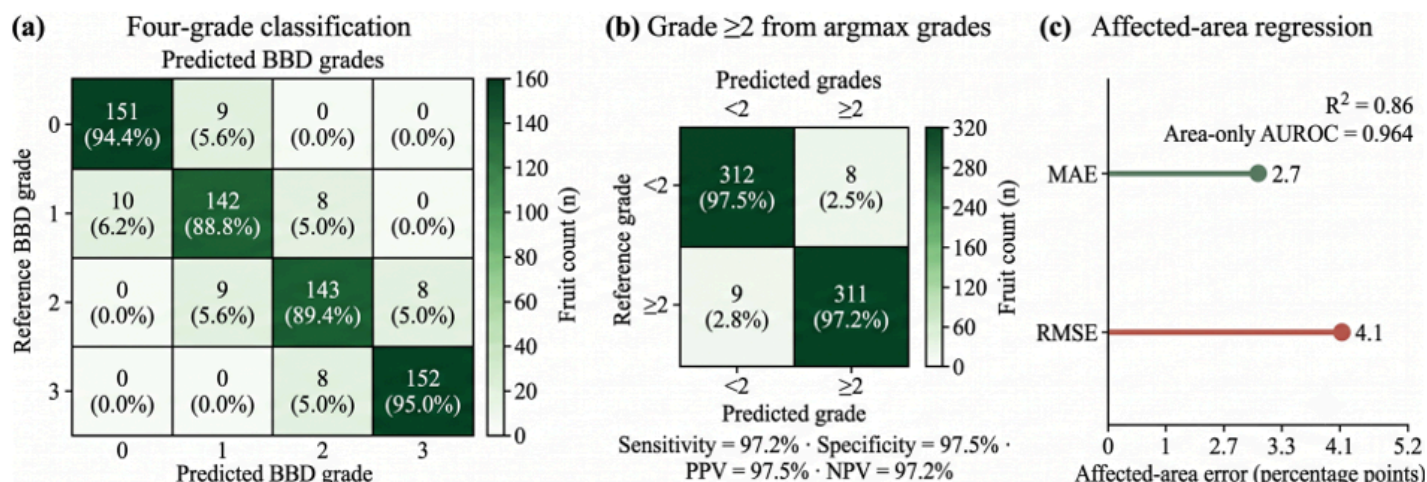


Figure 5

Out-of-fold predictive performance of PFT-ViT.

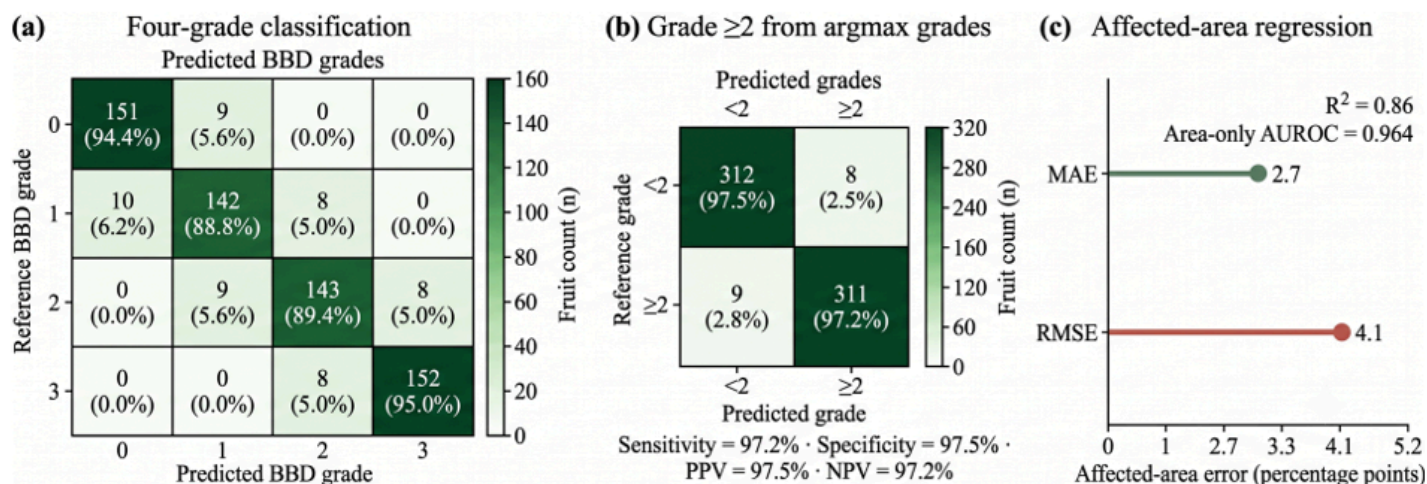


Figure 5

Out-of-fold predictive performance of PFT-ViT.

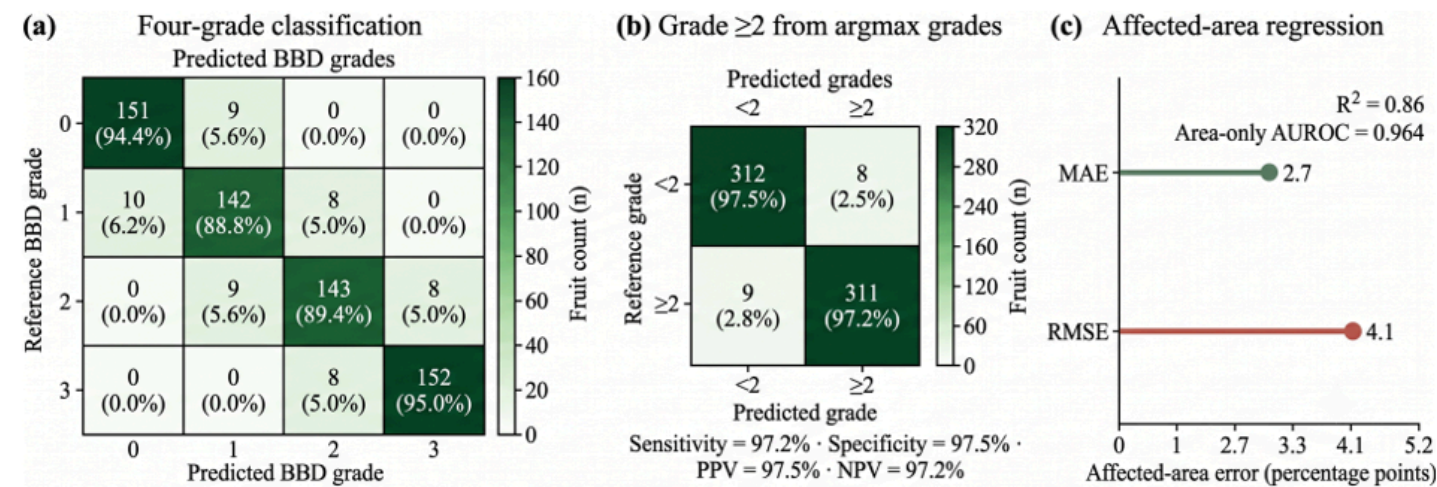


Figure 5

Out-of-fold predictive performance of PFT-ViT.

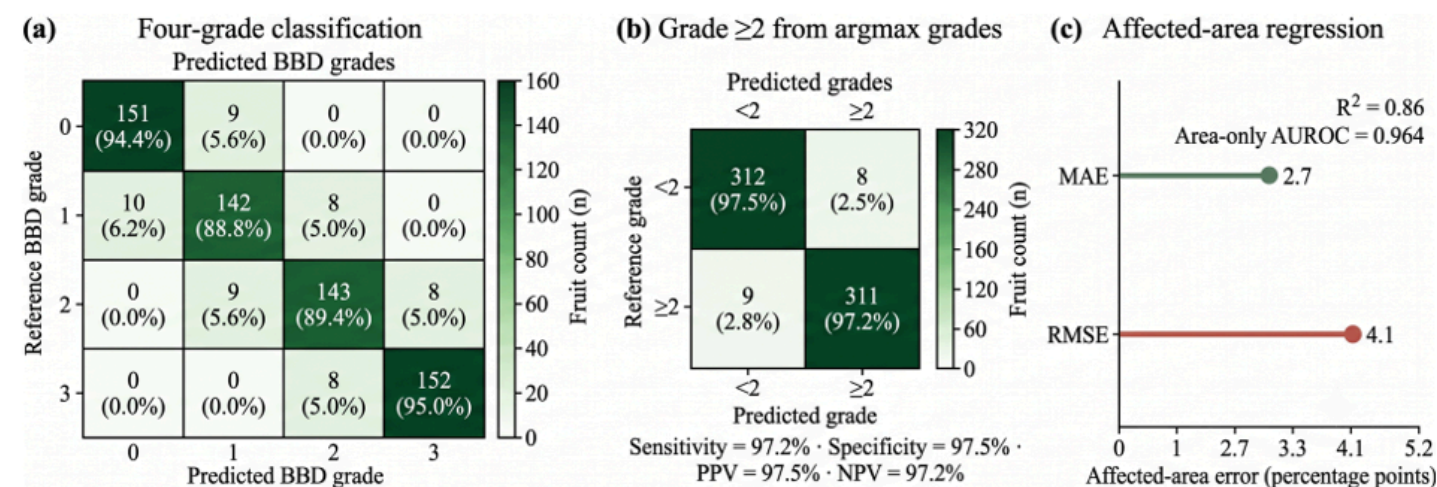


Figure 5

Out-of-fold predictive performance of PFT-ViT.

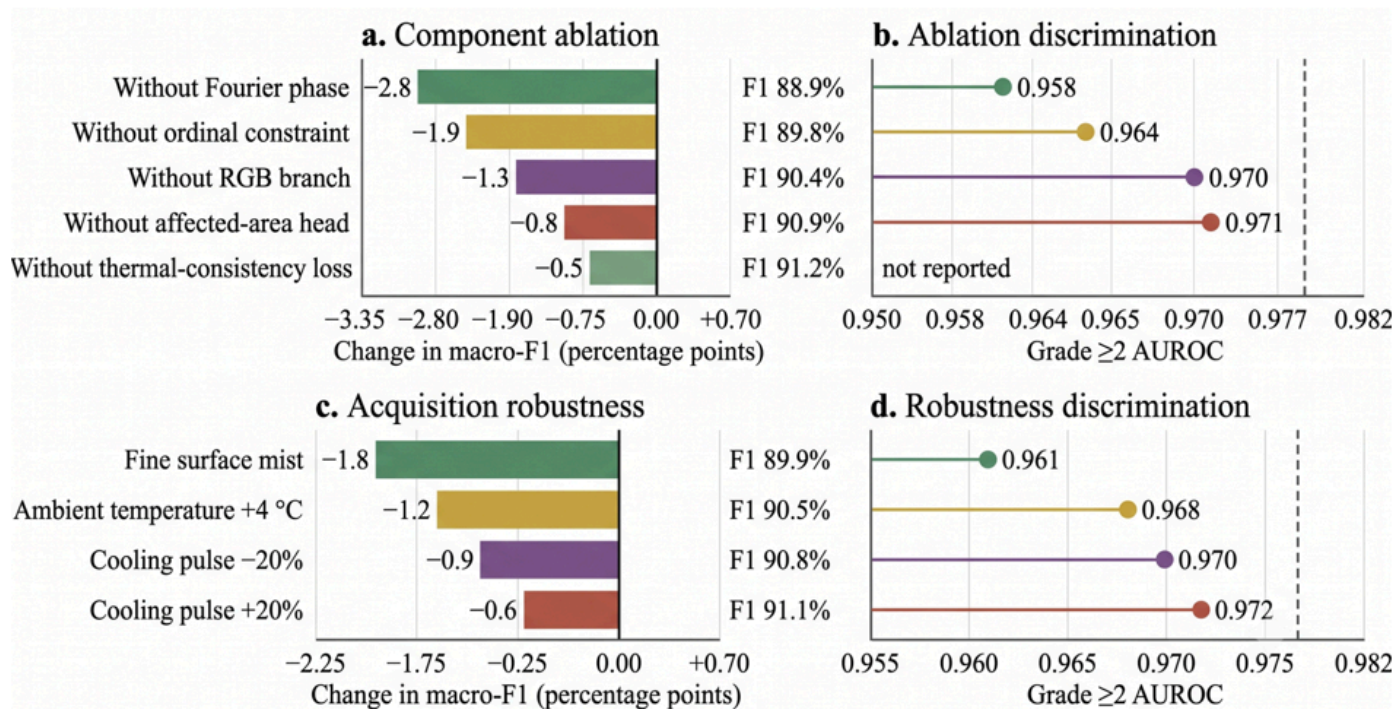


Figure 6

Component ablation and robustness of PFT-ViT under acquisition perturbations.

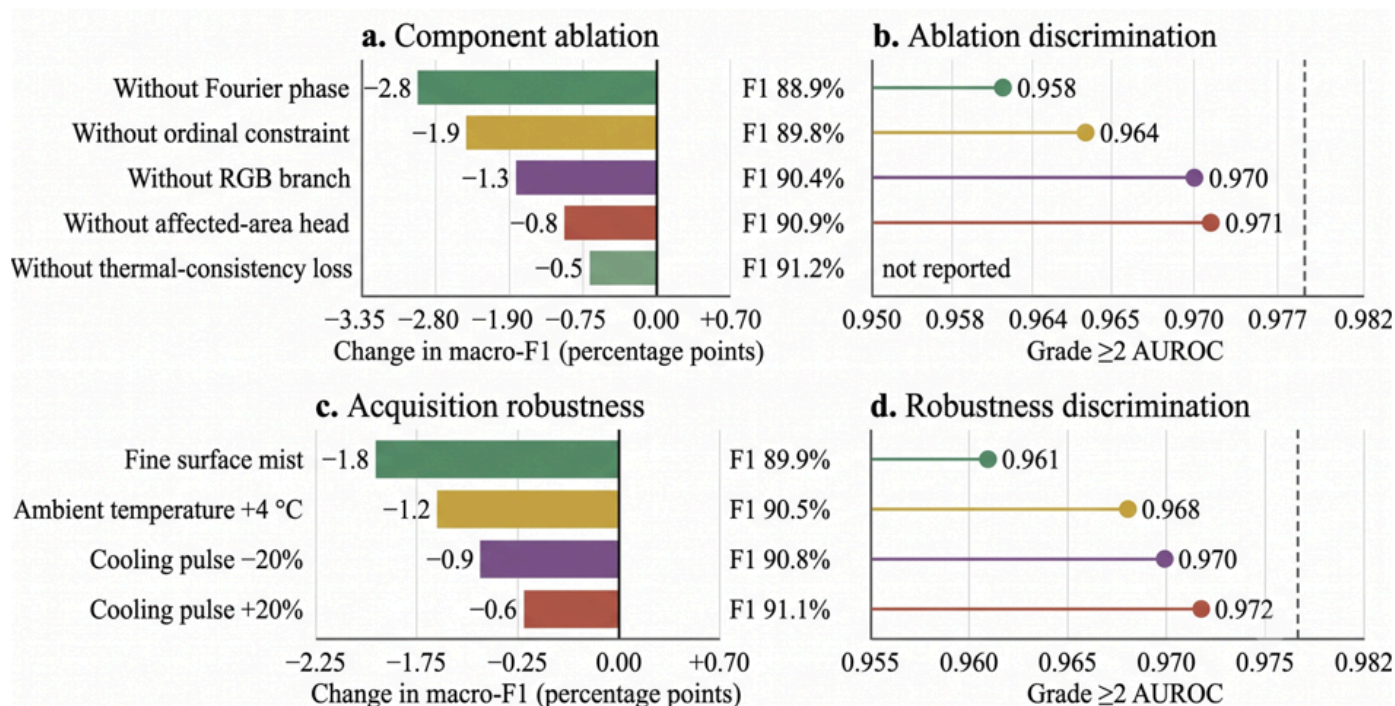


Figure 6

Component ablation and robustness of PFT-ViT under acquisition perturbations.

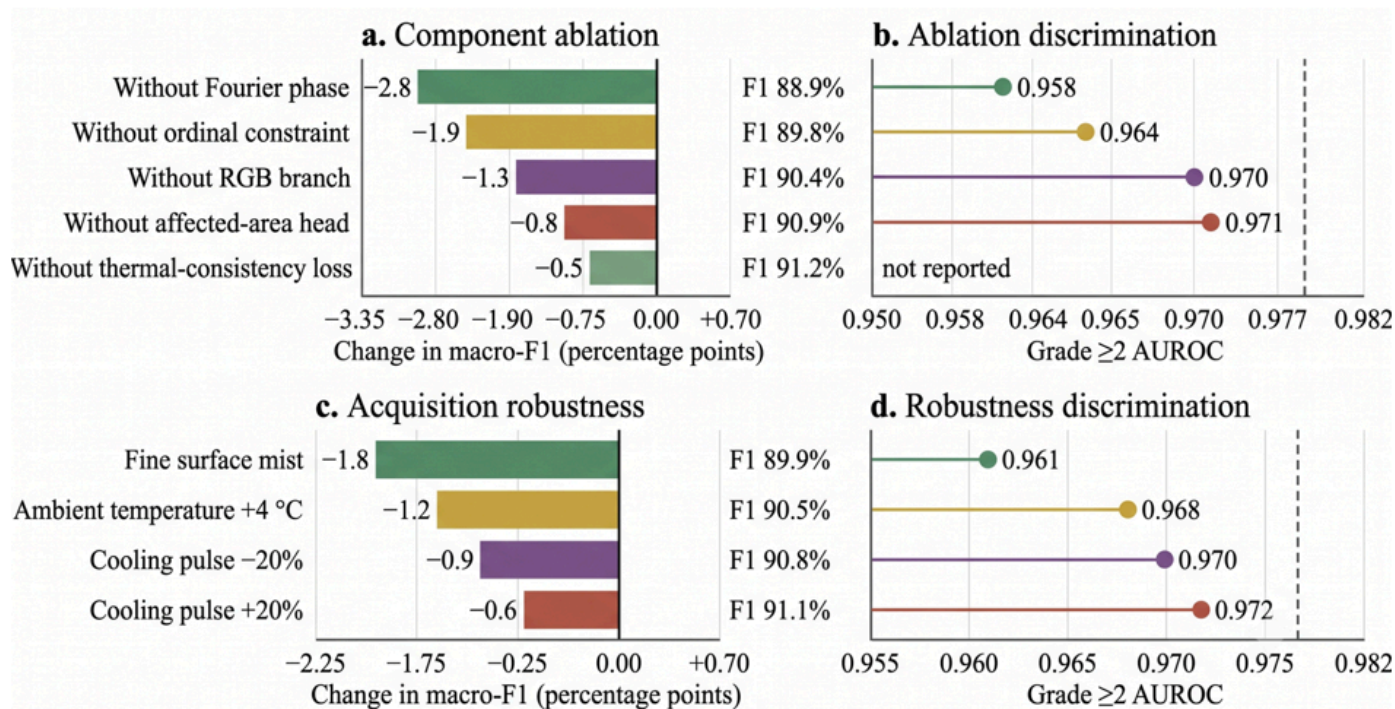


Figure 6

Component ablation and robustness of PFT-ViT under acquisition perturbations.

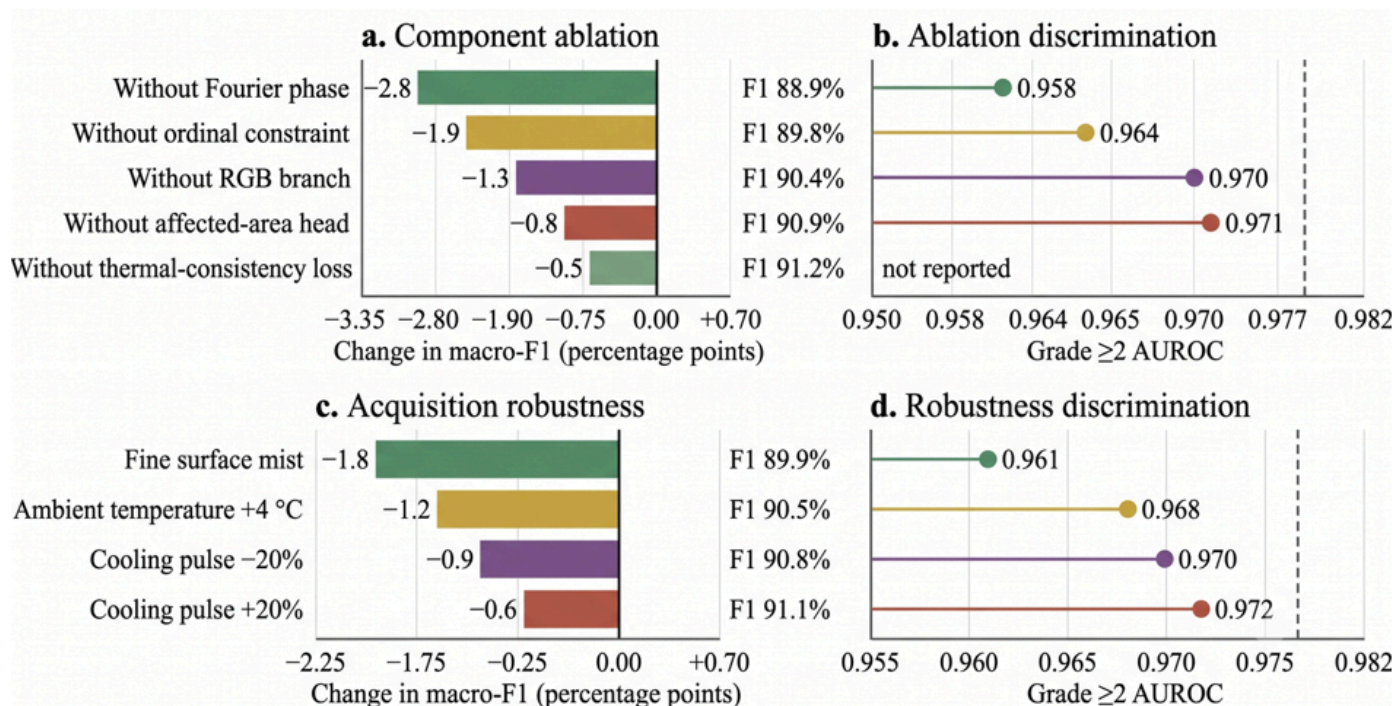


Figure 6

Component ablation and robustness of PFT-ViT under acquisition perturbations.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [GraphicalAbstract.png](#)
- [GraphicalAbstract.png](#)
- [GraphicalAbstract.png](#)
- [GraphicalAbstract.png](#)