

Article

Postharvest Storage Quality and Tissue-Specific Ginsenoside Distribution of Field-Sorted Fresh Ginseng as Affected by Packaging Film and Post-Wash Peracetic Acid During Subzero Storage

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Abstract

Fresh ginseng is a high-value medicinal root crop whose postharvest quality is affected by field heterogeneity, washing, packaging, and storage. This study evaluated two packaging films—50 μm polyethylene (PE50) and a 30 μm polyethylene/30 μm oriented polypropylene laminate (PE30/OPP30)—and a post-wash 80 ppm peracetic acid (PAA) spray applied at 20 °C at approximately 60 mL kg^{−1} fresh root mass. Field-sorted six-year-old roots from one commercial ridge were stored at −2 °C for 14 weeks. The primary factorial design comprised film and PAA treatment, while farmer grade class was retained as a stratification factor and tissue position as a within-root factor for destructive analyses. Package atmosphere, post-storage ambient CO₂ evolution, cumulative weight loss, tissue moisture, color and visual marketability, 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity, total phenolic content (TPC), and targeted liquid chromatography (LC) quantification of Rg1 and Rb1 were evaluated using three independent biological replicates. PE30/OPP30 generated lower O₂ and higher CO₂ than PE50 and reduced cumulative weight loss; however, O₂ reached 0.63% and CO₂ reached 14.04% at 4 weeks, indicating potentially hypoxic conditions. PAA did not consistently improve the measured physicochemical traits, and microbial efficacy was not evaluated. Fine roots showed the lowest moisture status but the highest Rg1 and Rb1 contents. These findings provide a single-field baseline for integrating packaging response, tissue water status, and chemical markers, but require validation across production sites, seasons, and packaging-film types before broad commercial application.

Keywords: medicinal root crop; passive modified atmosphere; hypoxic package atmosphere; water relations; antioxidant assays; commercial grading; quality assurance



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1. Introduction

Fresh 6-year-old ginseng (*Panax ginseng* C.A. Meyer) is a high-value medicinal root crop, but its fresh-market value can deteriorate rapidly during the sequence from harvest

to washing, drying, packaging, storage, and distribution. Unlike many fresh commodities, marketability of fresh ginseng is determined not only by whole-root mass, but also by the visual integrity of the rhizome head, main root body, lateral roots, and fine roots. Mechanical injury and epidermal disruption during postharvest handling can promote water loss, tissue softening, discoloration, and decay, making moisture management a central determinant of fresh ginseng storability [1–5].

In Korean distribution chains, subzero storage around $-2\text{ }^{\circ}\text{C}$ is commonly used to slow quality deterioration, but storage temperature alone does not determine quality retention. Fresh ginseng studies have shown that excessively low storage temperatures can aggravate physiological disorder symptoms during subsequent distribution, whereas simulated export and distribution conditions can accelerate softening and fungal decay depending on package unit and temperature history [6,7]. A related work also shows that storage substrate, film packaging, gas composition, and storage duration can influence quality trajectories in fresh ginseng or closely related ginseng materials [8–11]. Recent kinetic and multivariate shelf life studies further emphasize that practical plastic film packaging and systematically collected quality data are needed to predict fresh ginseng storability under distribution-relevant conditions [12]. In fresh ginseng, the reported response at $-4\text{ }^{\circ}\text{C}$ included increased respiration and ethylene production, elevated electrolyte leakage, and greater browning and decay during subsequent distribution, which is more consistent with subfreezing- or freezing-related membrane injury than with classical chilling injury. Intracellular ice formation was not directly measured and is, therefore, not claimed as the demonstrated mechanism.

Film packaging is, therefore, a central intervention because the in-package atmosphere is not determined by the film name alone. It is a realized outcome of product respiration, film gas permeability, water vapor transfer, package geometry, surface moisture, and temperature history. Modified-atmosphere packaging can reduce dehydration and delay deterioration, but its performance must be interpreted in relation to commodity-specific respiration and water relations [13–17]. In fresh ginseng, this point is particularly important because fine roots have a high surface-to-volume ratio and may respond differently from the main root body or rhizome head.

Washing is another unavoidable step in fresh ginseng handling because it removes soil and improves appearance, but washing can also create hygiene risks when the process water is not properly controlled. Peracetic acid (PAA) has been proposed as an alternative sanitizer to chlorine in fresh produce systems, with evidence of industrial-scale antimicrobial performance and lower concern over chlorinated disinfection by-products [18,19]. However, PAA efficacy and product response depend on organic load, contact time, physicochemical conditions, surface state, and application mode [20–22]. Washing, coating, and packaging interventions in fresh ginseng have already shown that post-wash handling can shape product quality, but a post-wash PAA surface spray followed by final ambient air-drying should not be assumed to improve physicochemical quality unless it is evaluated under the same packaging and storage conditions used in practice [2,23,24]. PAA acts primarily as an oxidizing antimicrobial agent through damage to microbial membranes, proteins, and other cellular components. Direct evidence that an 80 ppm spray disrupts the protective periderm or cork layer of fresh-ginseng roots is unavailable; any effect on root water loss, therefore, remains a hypothesis requiring anatomical or permeability measurements.

Fresh ginseng quality assurance also requires a grading language that can connect laboratory storage data with field marketing practice. In Korea, public fresh ginseng grading is provided through the National Agricultural Products Quality Management Service agricultural product grade standards, which include Korean size grade categories translated here as extra-large, large, medium, and small [25]. In farmer-level sales, however,

roots are commonly sorted using a more differentiated seven-class logic that considers size together with branching, fibrous-root development, visual integrity, and intended use. For food quality research, this mismatch is not only a regulatory issue, but also a sampling problem: if experimental lots are pooled or described only by broad size codes, the morphological heterogeneity that determines water loss, marketability, and chemical-marker distribution may be obscured [26]. Tissue-resolved moisture status and targeted markers such as ginsenosides Rg1 and Rb1 can, therefore, strengthen postharvest quality profiling by linking external grading traits with internal chemical quality [27–31].

Therefore, this study evaluated fresh ginseng as a field-to-package food quality system rather than as a uniform pooled root commodity. A field-derived seven-class sorting scheme was retained to preserve farmer-level heterogeneity, and PE50 and PE30/OPP30 films were compared with washed-control and PAA-sprayed treatments during -2°C storage. Package atmosphere, post-storage CO_2 evolution, cumulative weight loss, tissue moisture, visual quality, DPPH radical scavenging activity, total phenolic content, and targeted LC-based Rg1/Rb1 contents were analyzed together. The aim was to identify which quality axes were controlled mainly by packaging, which were tissue-dependent, and how these responses can support more practical quality assurance and storage management for fresh ginseng as a high-value fresh food.

2. Materials and Methods

2.1. Field Site, Plant Material, and Harvest

Six-year-old fresh ginseng roots were harvested from a cooperating commercial field in Chungju, Chungcheongbuk-do, Republic of Korea ($36.953634^{\circ}\text{N}$, $127.762956^{\circ}\text{E}$), near the Department of Herbal Crop Research, National Institute of Horticultural and Herbal Science, Eumseong. The roots were collected from one contiguous field segment within a single ridge/tractor-lane area. Because the material originated from one field segment and one harvest lot, it was handled as a single field-derived commercial lot rather than as independent farm populations. This design preserved realistic within-lot variation in root size, branching, fibrous-root development, and visual integrity while limiting inference to the production environment studied.

2.2. Farmer-Grade Sorting, Treatment Structure, and Biological Replication

Immediately after harvest, the roots were sorted into seven farmer grade classes: Extra, Large, Medium, Small, Mixed, Large samgyetang, and Small samgyetang. The samgyetang classes comprised smaller whole roots marketed for use in samgyetang (Korean whole-chicken soup); Large and Small samgyetang distinguished the larger and smaller root-size fractions within this end-use category. The public Korean fresh ginseng size grades, translated here as extra-large, large, medium, and small, were used only as the national grading context and were not experimental treatment levels. The primary factorial treatment structure comprised two films (PE50 and PE30/OPP30) and two post-wash treatments (washed control and 80 ppm PAA spray). Farmer-grade class was retained as a pre-specified stratification/adjustment factor because it represented the commercial heterogeneity of the harvested lot. Tissue position (rhizome head, main root body, lateral roots, and fine roots) was treated as a within-root factor for destructive tissue analyses.

Experimental Units and Sample Allocation

Three independent biological replicates were used for each film $\times$ post-wash treatment $\times$ farmer grade class combination at each sampling week. For package-level measurements, the independent package was the experimental unit. The repeated cumulative weight loss cohort comprised 84 packages (2 films $\times$ 2 post-wash treatments $\times$ 7 classes $\times$ 3 package replicates). Each

package contained 1 Extra, 3 Large, 4 Medium, 8 Small, 10 Mixed, 10 Large samgyetang, or 15 Small samgyetang roots, corresponding to 612 roots in the longitudinal weight loss cohort. Cumulative weight loss was measured repeatedly on these same packages throughout storage. Headspace, respiration, and destructive tissue analyses used packages allocated to the respective sampling week. For destructive analyses, each replicate was a separately prepared package-derived tissue composite; the three replicates remained separate throughout tissue dissection, freeze-drying, grinding, storage, and analysis. The exact number of individual roots contributing to each pooled tissue composite was not retained after sorting and pooling. Repeated instrument readings, microplate wells, and LC injections were treated as technical subsamples, and were not counted as independent biological replicates.

2.3. Commercial Washing, Post-Wash Treatment, and Final Drying

The roots were processed using a commercial washing system representative of local postharvest practice, including pre-wash rinsing, loading onto a mesh conveyor, commercial washing, and in-machine draining/drying. After in-machine draining/drying, the roots were assigned to the washed-control or PAA treatment. The 80 ppm PAA working solution was applied immediately in a processing room maintained at 20 °C when no visible free surface water remained. The temperature of the working solution itself was not measured separately. The entire 3 L working solution was applied to approximately 50 kg of fresh roots using a hand-held sprayer, corresponding to approximately 60 mL kg⁻¹ fresh root mass. The roots were alternately exposed on the front and back surfaces to improve coverage. After the treatment assignment, all roots were air-dried on trays under ambient processing room conditions for approximately 24 h before packaging.

2.4. Packaging Films and Storage

The PE50 treatment used a single-layer polyethylene film with a nominal thickness of 50 µm. The PE30/OPP30 treatment used a laminate comprising 30 µm polyethylene and 30 µm oriented polypropylene (total nominal thickness, 60 µm). Archived institutional OTR and WVTR records were available for coded packaging development candidates and component films (Table S6), but the sample-code crosswalk to the exact film lots used in this storage experiment could not be recovered; the CO₂ transmission rate was not determined. Accordingly, no archived numerical value was assigned as a lot-specific property of PE50 or PE30/OPP30, and the film response was interpreted from the measured package atmosphere. The roots were packed in 30 × 40 cm bags and stored at −2 °C. Nominal sampling weeks were 0, 4, 6, 8, 10, 12, and 14 weeks.

2.5. Field Workflow Documentation

The field-derived sorting and postharvest sequence is documented in Figure 1, and the public grading context, farmer grade classes, package composition, treatment factors, and sampling schedule are summarized in Table 1.

2.6. In-Package Gas Composition and Post-Storage CO₂ Evolution Response

In-package O₂ and CO₂ concentrations were measured at each sampling week using three independent packages per combination. For the post-storage CO₂ evolution assay, each of the seven farmer grade classes was measured in a separate airtight chamber; roots from different classes were not pooled. Three independent package-derived biological replicates were measured per film × PAA × grade class × sampling week combination. Before analysis, packages were transferred from −2 °C to 5 °C, and held for 24 h. The roots were then enclosed for 60 min under ambient laboratory conditions. Because chamber temperature was not instrumentally recorded, the values were interpreted as a post-storage

ambient CO₂ evolution response following 5 °C equilibration, not as direct respiration at −2 °C or inside the packages.

Table 1. Public grading context, farmer grade structure, package composition, treatment factors, and sampling design.

Category	Level/Description	Role or Notes
Public grading context	Korean public fresh ginseng size grade categories, translated here as extra-large, large, medium, and small	National grading context only; not an experimental treatment factor
Farmer grade class	Extra	Largest/highest commercial farmer-grade class in this study
Farmer grade class	Large	Farmer-relevant commercial class
Farmer grade class	Medium	Farmer-relevant commercial class
Farmer grade class	Small	Farmer-relevant commercial class
Farmer grade class	Mixed	Morphologically heterogeneous commercial class
Farmer grade class	Large samgyetang	Larger roots within the class marketed for whole-root use in samgyetang (Korean whole-chicken soup)
Farmer grade class	Small samgyetang	Smaller roots within the class marketed for whole-root use in samgyetang
Packaging film	PE50; single-layer PE, 50 µm	Reference film treatment
Packaging film	PE30/OPP30 laminate; PE 30 µm/OPP 30 µm	Laminated film treatment; total nominal thickness 60 µm
Post-wash treatment	Washed control	Commercial washing, in-machine draining/drying, and final ambient air-drying
Post-wash treatment	80 ppm PAA surface spray	Applied at 20 °C at approximately 60 mL kg ^{−1} fresh root mass before final drying
Storage	−2 °C for 14 weeks	Nominal sampling weeks: 0, 4, 6, 8, 10, 12, and 14
Package size	30 × 40 cm	Used for all film treatments
Biological replication	Three independent packages or package-derived composites	Defined separately for each response variable; see Table S7

2.7. Cumulative Weight Loss and Tissue Moisture

Cumulative weight loss was calculated as $[(FW_0 - FW_t)/FW_0] \times 100$, where FW_0 is initial package mass and FW_t is package mass at storage week t . The same three independent package units were followed longitudinally. For tissue moisture, separately allocated packages were destructively sampled. Each package-derived biological replicate was separated into rhizome head, main root body, lateral roots, and fine roots. Fresh weight and freeze-dried weight were recorded, and the moisture content was calculated as $[(FW - DW)/FW] \times 100$.

2.8. Surface Color, Root Thickness, Decay, and Visual Marketability

Surface color was expressed as CIE L*, a*, and b* values, and main-root thickness was measured using a standardized position. Visual marketability was assessed using product inspection descriptors without tasting or consumer testing. Decay-related observations were recorded using the study defect scale; score 5 represented complete decay, whereas score 4 denoted severe softening, mold, or decay-like deterioration. Because pathogens

were not isolated, these observations are reported as visual deterioration rather than microbiologically confirmed decay.



Figure 1. Field-relevant postharvest workflow and farmer grade classification used in this study. Panels show (A) field harvest, (B) a heterogeneous harvested lot, (C) preliminary farmer-used grade sorting, (D) seven-grade commercial classification, (E) pre-wash rinse, (F) loading onto the mesh conveyor of the commercial washer, (G) commercial washing and in-machine draining/drying, and (H) final ambient air-drying on trays (~24 h).

2.9. DPPH Radical Scavenging Activity

DPPH radical scavenging activity was determined colorimetrically using freeze-dried ginseng extracts and interpreted as an electron-transfer antioxidant response, consistent with established principles and limitations of in vitro antioxidant assays [32,33]. Standards were prepared using a 4-fold dilution scheme, whereas samples were analyzed after 10-fold dilution. Values were back-calculated to the original extract basis. An analytical plate was retained during data processing, and within-plate standardization was used for cross-plate visualization and association analysis.

2.10. Total Phenolic Content

Total phenolic content (TPC) was determined using the Folin–Ciocalteu assay. Because the reagent has broad redox reactivity and is not phenolic-specific, the results were interpreted cautiously [33,34]. Freeze-dried ginseng powder was extracted and analyzed after 10-fold dilution, with values back-calculated to the original extract basis. Because standard-curve slopes differed between analytical plates and the Folin–Ciocalteu reagent is not phenolic-specific, plate-standardized values were used for comparative inference, while original-basis values are reported descriptively.

2.11. Targeted LC Quantification of Ginsenosides Rg1 and Rb1

Freeze-dried tissue powder (0.5 g) was extracted with 70% methanol (5 mL). No additional dilution was applied before the LC injection. Rg1 and Rb1 were quantified using external standards [27–31] and were interpreted as targeted ginsenoside markers rather than as a complete ginsenoside profile [35]. concentrations were converted to dry-sample units using the extraction ratio ($\mu\text{g g}^{-1}$ dry sample = $\text{mg L}^{-1} \times 10$). Two additional roots

showing softening during storage were analyzed as exploratory checks and excluded from the balanced inferential analyses.

2.12. Statistical Analysis

Response-specific models were used. Packaging film, PAA treatment, storage week, and farmer grade class were fixed effects for package-level responses. For cumulative weight loss, package identity was included as a random intercept because the same package was measured repeatedly. Headspace and post-storage CO₂ evolution used independently allocated packages at each week; biological replicate was treated as a random/block effect. Tissue position was an additional fixed within-composite factor for tissue moisture, DPPH, TPC, Rg1, and Rb1, and package-derived composite replicate was included as a random/block effect. Analytical plate was included as a blocking factor for DPPH and TPC. Rg1 and Rb1 were analyzed on the log₁₀ scale. Tukey-adjusted pairwise comparisons were used for mean separation at $\alpha = 0.05$. Pearson and Spearman correlations were used for DPPH–TPC and Rg1–Rb1 associations. Trait-wise z-score standardization and tissue-level heatmap visualization were used as descriptive integrative tools, following established metabolomics data-integration and multivariate-analysis principles [36–38]. Statistical analyses were performed using Python 3.13.5 with pandas 2.2.3, SciPy 1.17.0, and statsmodels 0.14.6; figures were generated using Matplotlib 3.10.8. Exact or threshold *p*-values for principal effects are reported in the Results, with full model outputs and pairwise comparisons in Tables S2 and S4.

3. Results

3.1. In-Package Gas Composition

Packaging film was the clearest determinant of package atmosphere. At 4 weeks, PE30/OPP30 packages reached O₂ concentrations of 0.63–3.96% and CO₂ concentrations of 12.07–14.04%, whereas PE50 packages maintained O₂ at 9.91–14.00% and CO₂ at 2.43–2.81% (Figure 2). Film and film $\times$ storage week effects were significant for both O₂ and CO₂ ($p < 0.001$), whereas the PAA main effect was not significant for O₂ ($p = 0.492$) or CO₂ ($p = 0.295$) (Tables 2 and S2). The 0.63% O₂ condition is described as potentially hypoxic because fermentative metabolites were not measured.

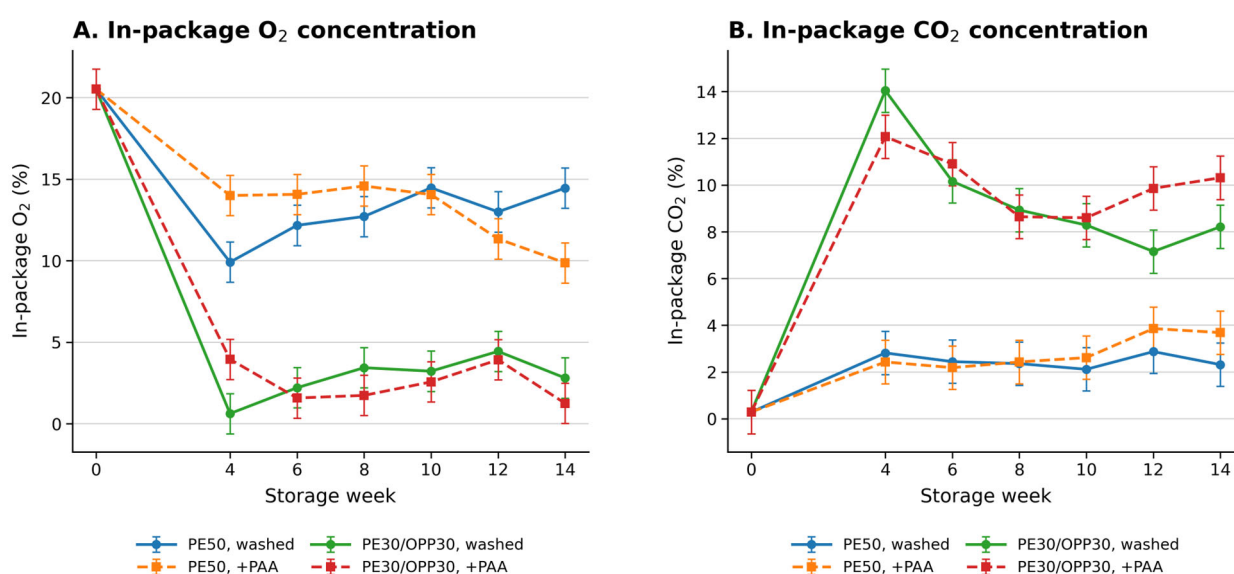


Figure 2. Adjusted means $\pm$ SE for in-package O₂ (A) and CO₂ (B) during 14 weeks of storage. Full fixed-effect tests and Tukey-adjusted comparisons are provided in Tables 2, S2 and S4.

Table 2. Selected inferential tests for package-level storage responses. Complete model output is provided in Table S2.

Response	Effect	<i>p</i> -Value	Tukey-Adjusted Interpretation
Headspace O ₂	Film	<0.001	PE30/OPP30 lower than PE50
Headspace O ₂	PAA	0.492	Not significant
Headspace O ₂	Film × week	<0.001	Film separation changed over time
Headspace CO ₂	Film	<0.001	PE30/OPP30 higher than PE50
Headspace CO ₂	PAA	0.295	Not significant
Headspace CO ₂	Film × week	<0.001	Film separation changed over time
Post-storage CO ₂ evolution	Film/week/selected interactions	See Table S2	Treatment comparisons interpreted within sampling week
Cumulative weight loss	Storage week	<0.001	Loss increased over storage
Cumulative weight loss	Film and PAA terms	See Table S2	PE50 + PAA was highest at 14 weeks

3.2. Post-Storage CO₂ Evolution and Cumulative Weight Loss

The post-storage CO₂ evolution response did not mirror package atmosphere in a one-to-one manner (Figure 3A). Because the roots were equilibrated at 5 °C for 24 h and then assayed under unrecorded ambient laboratory conditions, these values are interpreted as an operational post-storage response rather than direct subzero respiration. Cumulative weight loss increased with storage week ($p < 0.001$), and film and PAA effects were detected in the longitudinal model (Tables 2 and S2). At 14 weeks, PE50 + PAA showed the greatest adjusted cumulative loss (1.036%), whereas the PE30/OPP30 treatments remained lower (0.705–0.716%) (Figure 3B).

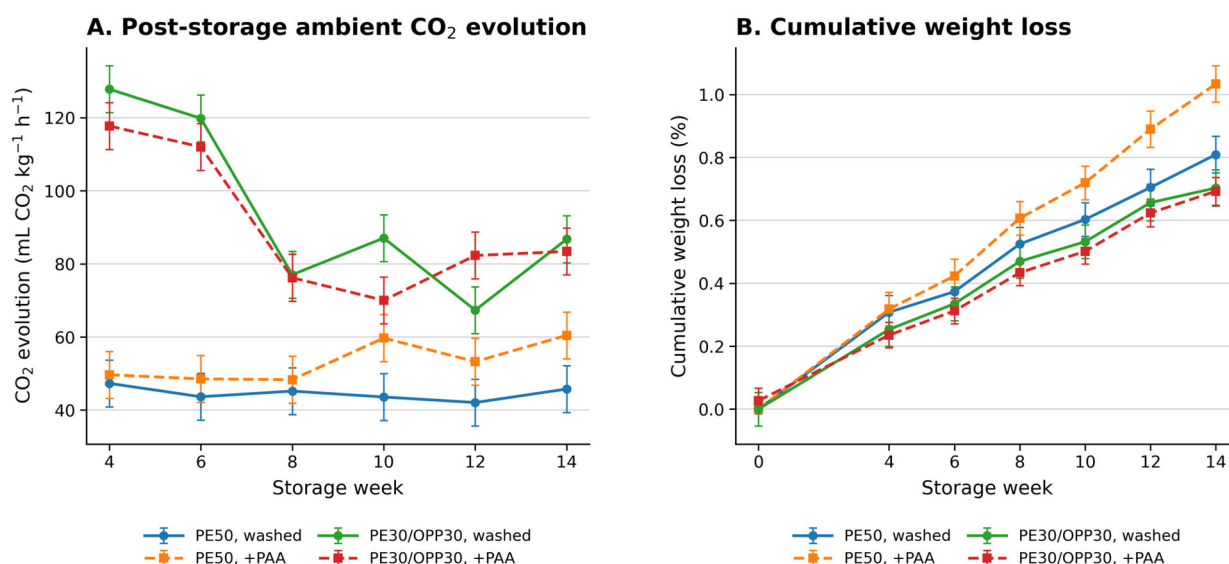


Figure 3. Adjusted means $\pm$ SE for post-storage ambient CO₂ evolution (A) and cumulative weight loss (B). Cumulative weight loss was monitored repeatedly within the same three packages; package identity was included as a random intercept. The full model and Tukey results are provided in Tables 2, S2 and S4.

3.3. Tissue Moisture

Tissue position strongly affected moisture status ($p < 0.001$), with fine roots showing the lowest means and the greatest temporal variability (Figure 4A). In the fine-root subset, PAA and storage week were significant (both $p < 0.001$), and the PAA $\times$ storage week interaction was also significant ($p = 0.015$) (Tables 3 and S2). At 8 weeks, adjusted fine-root moisture

was 52.53% for PE50-washed, 42.89% for PE50 + PAA, 53.83% for PE30/OPP30-washed, and 36.41% for PE30/OPP30 + PAA (Figure 4B).

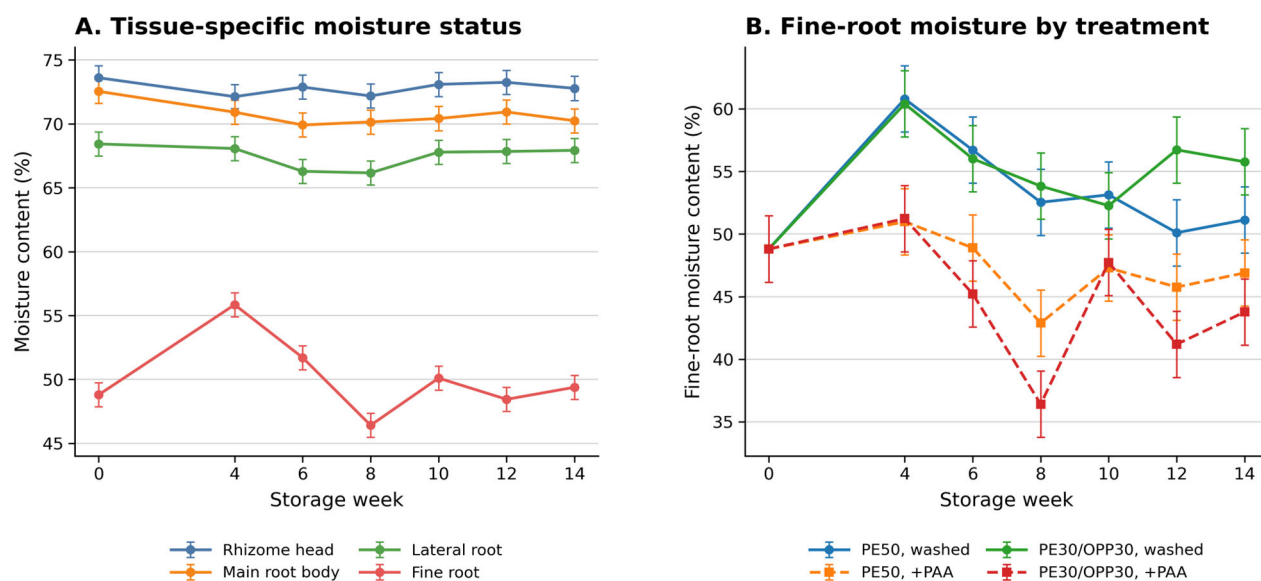


Figure 4. Adjusted means $\pm$ SE for moisture by tissue position (A) and fine-root moisture by film and PAA treatment (B). Tukey-adjusted comparisons are summarized in Tables 3 and S4.

Table 3. Selected inferential tests and mean separation interpretation for tissue moisture. The complete output is provided in Tables S2 and S4.

Analysis	Effect	<i>p</i> -Value	Tukey-Adjusted Interpretation
All tissues	Tissue position	<0.001	Rhizome head and main root body retained more moisture; fine root was lowest
All tissues	Storage week	<0.001	Moisture changed over storage
All tissues	Tissue $\times$ week	<0.001	Temporal response differed among tissues
Fine-root subset	PAA	<0.001	PAA response depended on storage context
Fine-root subset	Storage week	<0.001	Strong temporal response
Fine-root subset	PAA $\times$ week	0.015	Treatment separation varied by week

3.4. Color, Visual Marketability, and Decay-Related Observations

Color and visual marketability changed more gradually than package atmosphere and tissue moisture. No sample reached a score of 5 (complete decay) during the experiment. Three score 4 observations (severe softening, mold, or decay-like deterioration) were recorded: PE50-washed Small at 6 weeks, PE50-washed Small samgyetang at 8 weeks, and PE30/OPP30 + PAA Small at 8 weeks. Because pathogens were not isolated, these events are reported as visual deterioration rather than microbiologically confirmed decay.

3.5. DPPH Radical Scavenging Activity and Total Phenolic Content

Tissue position significantly affected plate-standardized DPPH and TPC responses ($p < 0.001$). The rhizome head had the highest adjusted values, whereas the main root body had the lowest; Tukey groupings are shown in Tables 4 and S4. Across regular-design paired observations, DPPH and TPC were positively associated ($n = 475$; Pearson $r = 0.741$, $p < 0.001$; Spearman $\rho = 0.765$, $p < 0.001$) (Figure 5C).

Table 4. Tissue-level DPPH and TPC values and Tukey-adjusted mean separation groups.

Tissue	DPPH (ppm)	TPC (ppm)	n
Rhizome head	1544.6 ± 216.6 a	1356.0 ± 420.1 a	101
Main root body	880.9 ± 154.6 d	882.2 ± 295.2 d	101
Lateral root	1388.5 ± 265.2 b	1079.1 ± 359.4 b	100
Fine root	1116.0 ± 402.7 c	967.7 ± 295.1 c	100

Values are the mean ± SD on the original extract basis. Within each response column, different lowercase letters indicate Tukey-adjusted differences among tissues at $p < 0.05$. The DPPH–TPC association is shown in Figure 5C; plate-specific TPC calibration information is provided in Table S3.

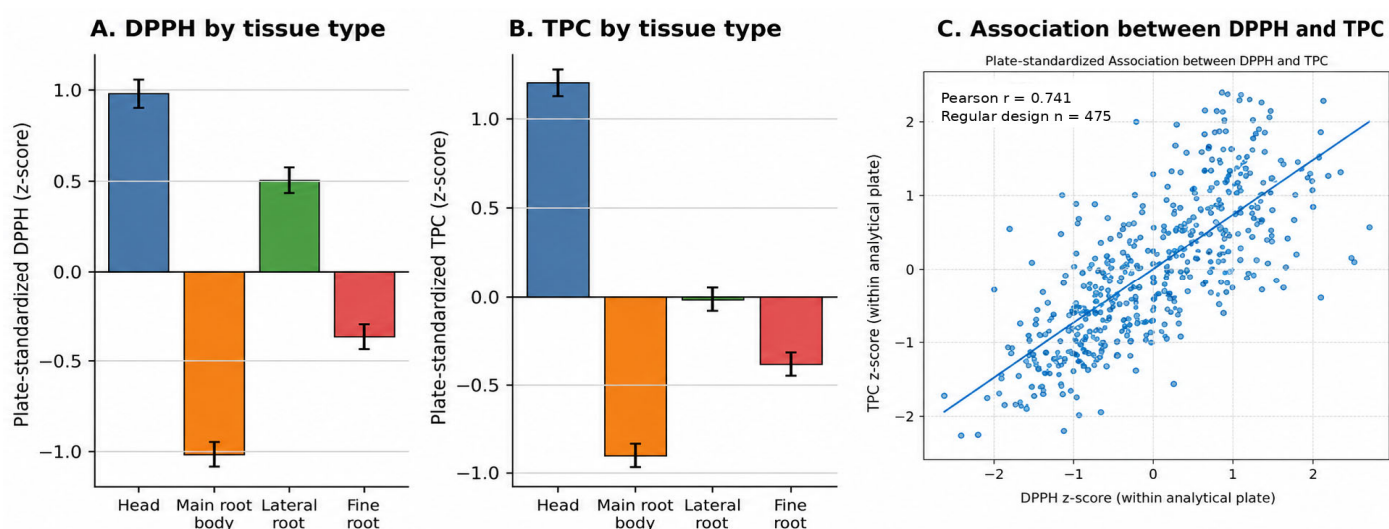


Figure 5. Tissue-specific plate-standardized DPPH (A) and TPC (B) adjusted means ± SE and their within-plate association (C). Different lowercase letters indicate Tukey-adjusted differences among tissues at $p < 0.05$; full comparisons are provided in Table S4.

3.6. Tissue-Specific Rg1 and Rb1 Distribution

Tissue position was the dominant source of variation in both Rg1 and Rb1 contents (both $p < 0.001$). Fine roots showed the highest concentrations of both ginsenosides, whereas the main root body showed the lowest values (Table 5; Figure 6A). Tukey-adjusted comparisons separated all four tissues for Rg1, with fine root, rhizome head, lateral root, and main root body assigned to groups a, b, c, and d, respectively. For Rb1, fine root was assigned to group A, rhizome head and lateral root to group B, and main root body to group C. Across 398 regular tissue-design observations, Rg1 and Rb1 were strongly positively associated (Pearson's $r = 0.855$; Spearman's $\rho = 0.848$; both $p < 0.001$; Figure 6B). Film × PAA and farmer grade class summaries are retained as secondary exploratory results in Table S1 rather than being interpreted as independent experimental designs. The integrated tissue-level heatmap illustrates that low fine-root moisture co-occurred with high targeted ginsenoside contents, whereas DPPH and TPC followed a different tissue ranking (Figure 6C).

Table 5. Tissue-specific Rg1 and Rb1 contents, and Tukey-adjusted mean separation groups.

Tissue	Rg1 ($\mu\text{g g}^{-1}$ Dry Sample)	Rb1 ($\mu\text{g g}^{-1}$ Dry Sample)
Rhizome head	7103.2 ± 143.8 b	5422.1 ± 320.9 B
Main root body	2958.4 ± 90.2 d	1904.7 ± 151.0 C
Lateral root	6388.7 ± 154.7 c	4902.6 ± 189.3 B
Fine root	11,519.1 ± 172.3 a	13,886.4 ± 358.4 A

Values are the adjusted means ± SE expressed as $\mu\text{g g}^{-1}$ dry sample. Within each ginsenoside column, the means followed by different letters differ significantly according to Tukey-adjusted pairwise comparisons at $p < 0.05$. Lowercase letters apply to Rg1, whereas uppercase letters apply to Rb1.

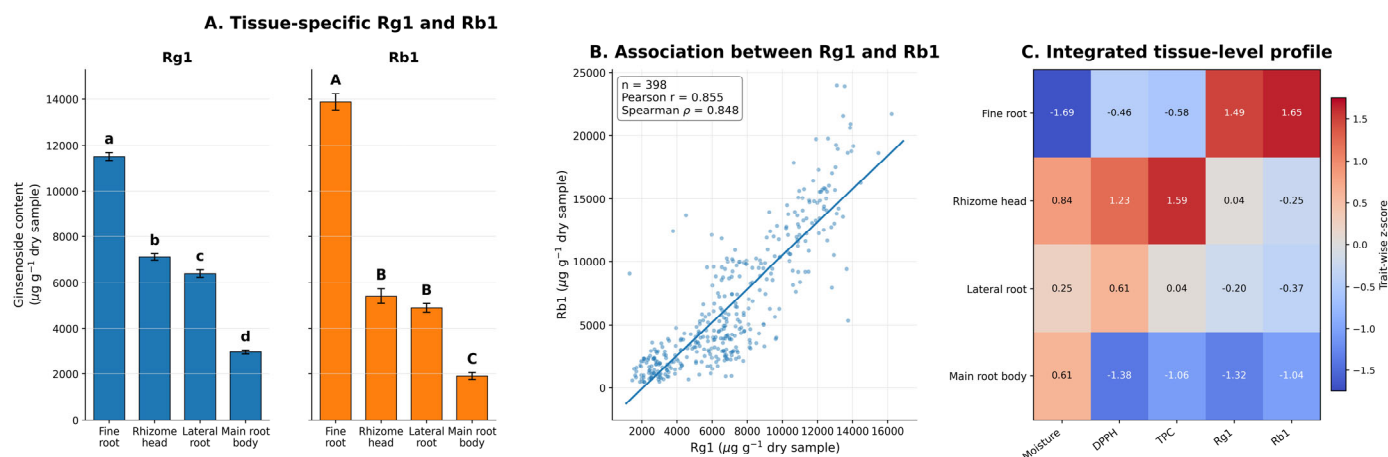


Figure 6. Tissue-specific distribution and association of ginsenosides Rg1 and Rb1 in fresh ginseng. (A) Tissue-specific adjusted means $\pm$ SE for Rg1 and Rb1. Within each ginsenoside, the means followed by different letters differ significantly according to Tukey-adjusted pairwise comparisons at $p < 0.05$; lowercase letters compare Rg1, whereas uppercase letters compare Rb1. Tissues in panel A are ordered by descending Rg1 mean. (B) Association between Rg1 and Rb1 across regular tissue-design observations ($n = 398$; Pearson's $r = 0.855$; Spearman's $\rho = 0.848$). (C) Tissue-level z-score heatmap integrating moisture content, DPPH, TPC, Rg1, and Rb1.

4. Discussion

This study does not propose the seven farmer grade classes as a replacement for public size grade categories. Instead, it provides a field-derived food quality layer that links public grading context with farmer-level sorting practice, packaging-driven storage response, tissue water status, and targeted chemical-marker distribution. The current Korean quality management specifications include size grade categories for fresh ginseng, translated here as extra-large, large, medium, and small, which support administrative simplicity and transaction-level communication. However, roots sold through farmer-level channels are not judged by size category alone: they are sorted, priced, and handled according to a composite of size, branching, fine-root development, visual integrity, and end-use. A grading system that ignores this field logic may be formally simple but biologically and commercially incomplete. By retaining seven farmer grade classes and measuring atmosphere, water relations, visual quality, antioxidant-related traits, and targeted ginsenosides, this work frames storability as a field-to-package food quality translation problem: how can public size grade categories be linked to the heterogeneous roots actually moving through postharvest handling? The continuous single-ridge field lot was important in this context because it preserved the within-lot size and morphology spectrum that farmers actually classify, rather than replacing commercial heterogeneity with artificially uniform roots. The framework is not presented as a finished national standard. It is an evidence-generating baseline for building one with multi-location validation, larger lots, and linkage to regulatory size grade categories [39–41].

The most actionable result is that packaging film controlled the realized package atmosphere and, in turn, the long-term mass conservation trajectory. PE30/OPP30 rapidly generated a lower- O_2 /higher- CO_2 environment than PE50 and was associated with lower cumulative weight loss at later storage intervals. This supports the view that film selection should be treated as an engineering decision fitted to commodity respiration, water vapor movement, package dimensions, product mass, surface wetness, and cold-chain temperature history, not as a nominal material choice [13,14,16,17,42,43]. The result also agrees with ginseng-specific evidence that modified-atmosphere packaging, surface coating, package configuration, and shelf-life modeling can alter fresh-ginseng quality trajectories during

storage and distribution [2,8,10,12,15,23]. The implication is important for industry: the relevant control variable is not simply whether a product is packaged, but whether the film package–product system generates a tolerable atmosphere and humidity regime for the commodity under the actual distribution temperature profile.

The minimum O₂ concentration of 0.63% at 4 weeks deserves caution. Such a severe low-O₂/high-CO₂ atmosphere may approach a commodity-specific threshold for fermentative metabolism. Ethanol, acetaldehyde, and other fermentation volatiles were not quantified, and no formal off-odor assessment was conducted. Accordingly, reduced weight loss under PE30/OPP30 should not be interpreted as proof that the atmosphere was physiologically optimal.

The respiration data sharpen this interpretation. The stronger modified atmosphere in PE30/OPP30 did not translate into consistently lower CO₂ evolution in the chamber assay. This should not be treated as a failure of the film effect. A chamber-based respiration index measured after package opening integrates the prior package atmosphere, tissue condition, gas diffusion during equilibration, and the measurement environment itself. In sealed packages, lower O₂ and higher CO₂ can still contribute to slower dehydration and reduced deterioration even if the post-storage chamber index is not proportionally lower. For fresh produce studies, this distinction is important because it prevents MAP performance from being collapsed into a single gas or respiration endpoint. It also explains why package evaluation should combine headspace gases, water loss, visible tissue condition, and commodity-specific quality markers rather than relying on respiration alone [17,44].

PAA should be interpreted cautiously. The treatment was sanitation-intended, but microbial counts, fungal incidence, sanitizer residues, and antimicrobial efficacy were not measured. PAA is an oxidizing antimicrobial agent, yet the present experiment did not assess periderm structure, cork-layer permeability, treatment-specific electrolyte leakage, or surface anatomy. Therefore, the lower moisture observed in some PAA-treated fine-root samples cannot be attributed mechanistically to disruption of the protective periderm. The data support only the conclusion that an 80 ppm post-wash spray did not provide a consistent physicochemical quality benefit under the tested conditions; its microbial efficacy and effects on root-surface integrity require separate validation. Previous fresh-produce studies indicate that sanitizer performance depends on treatment conditions, process configuration, organic load, and commodity surface properties [45–47], while fungal contamination has also been documented in fresh ginseng [48].

The tissue moisture results identify fine roots as the critical interface between physiology and marketability. The rhizome head and main root body retained higher moisture, but fine roots showed the lowest and most variable moisture status. This pattern is commercially meaningful because fine roots have a high surface-to-volume ratio, are easily injured during washing and packaging, and strongly influence the appearance of fresh ginseng. A package can show only modest whole-root mass loss while still allowing local dehydration in fine roots, and that localized dehydration may be what buyers visually perceive as quality decline. The result is consistent with broader postharvest evidence linking water loss, mechanical injury, epidermal disruption, transport conditions, and packaging environment with visible deterioration in fresh produce [3–5,49]. It also explains why grade-based fresh ginseng assessment should not rely only on package-level mass loss or main-root measurements: the most visually fragile tissue fraction may be the one that determines commercial downgrading.

The antioxidant results extend this tissue-level argument. The rhizome head showed the highest DPPH and TPC values, whereas the main root body was the lowest, and lateral and fine roots were intermediate. This pattern indicates that biochemical quality cannot be represented by whole-root averages when tissue identity is central to product

value. The within-plate standardization of DPPH and TPC was also essential. DPPH, ABTS, FRAP, and Folin–Ciocalteu-type assays are useful screening tools, but they differ in chemistry, response specificity, and susceptibility to matrix effects [32–34,50–52]. By standardizing within analytical plate, the DPPH-TPC association could be interpreted as a tissue-level redox/phenolic-equivalent relationship without overstating raw plate-to-plate differences. This is particularly important for ginseng tissues, where phenolic profiles, flavonoid-related compounds, and antioxidant activity vary among plant parts and cultivation histories [27,53].

The LC results are a decisive addition because they prevent a simplified antioxidant narrative and add a chemical marker layer to the grading framework. Rg1 and Rb1 were highest in fine roots and lowest in the main root body, whereas DPPH/TPC peaked in the rhizome head. This divergence is not contradictory. DPPH and Folin–Ciocalteu assays capture broad redox-active or phenolic-equivalent pools and are sensitive to assay chemistry and non-phenolic reducing substances [32,52,54], whereas Rg1 and Rb1 are targeted dammarane-type ginsenoside markers with compound-specific biosynthesis and tissue allocation [28–31,35,55]. The Rg1–Rb1 correlation and integrated heatmap make this point explicit: the two ginsenoside markers covaried strongly with each other, but their tissue pattern separated fine-root ginsenoside enrichment from rhizome-head antioxidant dominance. The film and PAA summaries should be read with the same discipline. PE30/OPP30 governed the realized package atmosphere and long-term mass conservation, but the LC data do not justify a strong claim that film packaging directly increased ginsenoside biosynthesis. Instead, film-related LC differences were secondary to tissue identity and farmer-grade architecture, and they may reflect indirect preservation of tissue condition under a modified atmosphere. Likewise, PAA should not be interpreted as a ginsenoside-enhancing treatment under the present design. The farmer grade pattern is important for standardization because classes used in field marketing differ in morphology and fine-root contribution; nevertheless, these class-level ginsenoside differences are descriptive and require a future class-balanced LC design before they can be converted into grading thresholds.

Several limitations constrain generalization. All roots originated from one contiguous ridge, one cooperating farm, and one harvest lot, and storage was evaluated only at -2°C ; the findings therefore represent a single-field baseline rather than a validated recommendation across production regions or seasons. The exact number of roots contributing to each destructive pooled tissue composite was not retained, although three package-derived biological replicates remained separate throughout processing and analysis. The respiration chamber temperature was not instrumentally recorded. Archived OTR and WVTR data existed for coded packaging development candidates, but the code-to-lot crosswalk for the exact study films could not be recovered, and CO_2TR was not measured. Finally, microbial efficacy, fermentative volatiles, off-odors, periderm integrity, and sanitizer residues were not quantified. Multi-site, multi-season, multi-lot validation with verified film transmission properties is required before broad commercial recommendations are made. More broadly, integrated shelf-life strategies combining packaging, temperature management, sanitation, and product-specific quality monitoring are increasingly emphasized for fresh and minimally processed produce [56].

Overall, the study supports a cautious field-to-package interpretation: fresh ginseng quality should not be inferred from sanitizer use, film name, whole-root weight loss, or grade label alone. Under the present single-field conditions, PE30/OPP30 produced the clearest packaging response by generating a more restrictive atmosphere and reducing cumulative weight loss, whereas the 80 ppm PAA spray did not provide a consistent physicochemical quality benefit. The seven farmer grade classes should be regarded as

a field-relevant stratification framework rather than a validated national grading system. This integrated interpretation supports future multi-site validation linking public size-grade categories, farmer grade practice, package atmosphere, fine-root water status, and tissue-specific chemistry.

5. Conclusions

Within this single-field, single-lot experiment, PE30/OPP30 generated a more restrictive low-O₂/high-CO₂ package atmosphere than PE50 and was associated with lower cumulative weight loss during 14 weeks at −2 °C. However, the extreme atmosphere observed at 4 weeks may have imposed hypoxic risk, which was not evaluated using fermentation metabolites or off-odor measurements. The 80 ppm PAA spray did not provide a consistent physicochemical quality benefit, and no conclusion can be drawn regarding antimicrobial efficacy. Fine roots combined the greatest dehydration susceptibility with the highest Rg1 and Rb1 contents, demonstrating that water status and targeted ginsenoside indicators describe complementary aspects of tissue quality. These findings provide a field-derived baseline for future validation; they should not be generalized into national grading or commercial storage recommendations without multi-site, multi-season, and multi-lot studies using verified film transmission properties.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12080940/s1>, Table S1: LC correlation, secondary film × PAA and farmer-grade summaries, and tissue-profile source values; Table S2: Response-specific model structures and ANOVA/mixed-model output; Table S3: DPPH–TPC association and analytical-plate standardization; Table S4: Tukey-adjusted pairwise comparisons and compact-letter groups for tissue-specific Rg1 and Rb1; Table S5: Detailed adjusted means formerly duplicated in the main-text tables; Table S6: Archived film-characterization records; Table S7: Experimental units, biological replication, and sample allocation.

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