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Original Paper

Extending the Shelf Life of Strawberries by Using UV Light Interference with New Packaging

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***Abstract*—This study investigated the effect of packaging material and ventilation opening location on strawberry (Fragaria ananassa) treated with UV-C light and stored at 4 °C over a 21-day period. Treatments comprised egg-crate trays made of Styrofoam or molded pulp with three opening locations (upper, lateral, or lower), all irradiated at an intensity of 964 µW/cm², together with a conventional polyethylene clamshell control. Styrofoam trays showed the lowest weight loss, followed by molded pulp, with the clamshell control highest ($P \leq 0.05$). Firmness, color, and odor were best retained in Styrofoam trays. Styrofoam packages remained free of visible mold through day 21, whereas control packages developed mold by day 11 and were withdrawn. Ventilation opening location had no significant effect on any measured attribute. Because UV-C was applied uniformly to every treatment, this design compares packaging systems within a UV-C-treated environment rather than isolating the contribution of irradiation itself. Within that constraint, UV-C-treated strawberries packaged in Styrofoam or molded pulp egg-crate trays retained acceptable quality substantially longer than those in conventional clamshell packaging.**

Keywords*—Packaging materials, Shelf life, Strawberry, UV-C treatment, Ventilation location

I. Introduction

Strawberries belong to the genus Fragaria in the rose family (Rosaceae). Strawberries gained attraction through their bright red color, which reflects maturity of the fruit. They are also a rich source of micronutrients and phytochemicals such as ascorbic acid and flavonoids [1, 2]. However, strawberry shelf life is very short; the fruit is fragile and perishable, making the handling and shipping process highly challenging.

The United States is the largest producer of strawberries worldwide, with California leading U.S. production, followed by Florida [3]. Americans consume approximately 3.4 pounds of fresh strawberries per capita [4]. Consumer awareness has increased regarding the quality criteria of fruits and vegetables, and demand for healthy produce free of chemicals and pesticides has also increased. Chlorine has been used as a sanitizing agent for fruits and vegetables; however, there are possible side effects including formation of carcinogens [5].

Several techniques have been investigated to reduce deterioration of strawberry during storage, through chemical treatments or exposing strawberry to UV light as a sterilization technique. UV light treatment has received wider acceptance among researchers and corporations compared to chemical applications that may leave residuals with potential side effects. UV light has shown a promising ability to retard cell wall degradation and inhibit enzymes involved in the ripening process of strawberry [6]. Terry and Joyce [7] reported that low doses of UV light can affect microorganism DNA, while also potentially causing structural damage to the plant.

In addition to UV and chemical treatment, techniques such as coatings and thermal treatment have been investigated; however, they were not as practical and cost effective as UV light. Packaging techniques are a crucial step to protect fruit from mechanical damage, ensure good ventilation inside the package, and protect the fruit from pathogen infections and insects [8]. In this research, we investigated the effect of packaging material and ventilation opening location on strawberry shelf life within a UV-C-treated system at 4 °C, which to our knowledge has not been previously reported.

II. Materials and Methods

A. Plant Material and Experimental Design

A total of 588 fresh strawberries of Chandler variety were collected from Bass Farm in Cobden, Illinois at 8 am. Selection criteria required 75% red color on the surface and freedom from mechanical injury and disease. Gloves were used to collect samples to reduce pathogen transmission. Packages were placed in large Styrofoam containers and transported by van with cool atmosphere to the walk-in cooling room at Southern Illinois University Carbondale (SIUC).

Strawberries were assigned to three packaging types: (1) egg-crate-shaped Styrofoam trays (Treatment A), (2) egg-crate-shaped molded pulp trays (Treatment B), and (3) conventional polyethylene clamshell packages serving as the control (Treatment C). Each package contained 12 fruits. For Treatments A and B, three ventilation opening locations were evaluated: upper (two 8 mm diameter holes), lateral (two 8 mm diameter holes), and lower (four 4 mm diameter holes), giving

six material × opening combinations (A1–A3, B1–B3) plus the clamshell control.

Each material × opening combination was replicated in independent packages arranged in a completely randomized design within the cooler with 3 replicates for each treatment. Packages designated for destructive sampling (total polyphenol content, total monomeric anthocyanin content, and microbial enumeration) were separate from those used for non-destructive weight and sensory measurements, so that repeated measurements were made on the same experimental units throughout storage. A total of 252 strawberries were used to measure weight loss, while the remaining fruits of the 588 were used for sensory evaluation, microbial analysis, and TPC and TMA determination.

Packages were maintained in a walk-in cooler held at 4 ± 1 °C and 80 ± 5% relative humidity. Temperature and relative humidity inside the cooler were recorded daily using an air conditioner unit (LG brand 18000 BTU) connected to a cool Bot adjusted at 4°c.

A UV light system was installed inside the cool room. The ultraviolet tunnel utilized lamps emitting a specific narrow wavelength spectrum of 254 nm, constructed of polished aluminum to reflect energy within the tunnel. Six UV lamps provided an intensity of 964 μW/cm². Weight, airflow, temperature, and humidity were recorded daily. A sensory test was conducted to assess mold formation and other attributes of strawberry quality including odor, color, and palatability. The experiment was terminated upon the first sign of mold.

Shelf life was defined operationally as the number of days of storage until the first visually detectable mycelial growth on any fruit within a package, assessed daily by the same panel under standardized lighting. Once mold was observed in a package, that package was withdrawn from the study and contributed no further weight, sensory, or compositional data. This endpoint is a microbiological spoilage endpoint rather than a consumer-rejection endpoint; sensory acceptability is reported separately, and in several treatments declined below the mid-point of the scale before visible mold appeared.

B. Total Polyphenol Content (TPC) Determination

Strawberry fruits were homogenized and polyphenols were extracted in a 70:29.5:0.5 v/v acetone, distilled water, and glacial acetic acid extraction buffer. The homogenate was placed in the extraction buffer within a shaker incubator for 2 hours and then centrifuged at 1640 g for 15 minutes. The pellet was extracted again for 1 hour and centrifuged after the supernatant was collected. Following filtration, total polyphenol content was determined spectrophotometrically. One mL of strawberry extract was mixed with 5 mL of Folin-Ciocalteu's reagent and 4 mL of 7% sodium carbonate and allowed to react for 1 hour. Absorbance was measured at 765 nm using a Thermo Scientific Genesys 10S UV-VIS Spectrophotometer. The TPC was expressed as mg of Gallic acid equivalents (mg GAE) per 100 g fresh weight from a standard calibration curve ($R^2 = 0.953$) of five Gallic acid standards (50, 100, 200, 500, and 1000 mg L^{-1}).

C. Total Monomeric Anthocyanin (TMA) Content Determination

The total monomeric anthocyanin content was determined using the method described by Giusti and Wrolstad [9]. Strawberry fruits were weighed, homogenized, and extracted for 0.5 hours in potassium chloride (pH = 1.0) and sodium acetate (pH = 4.5) buffers. Absorbance of the extracted solution was measured at 520 nm and 700 nm using a Thermo Scientific Genesys 10S UV-VIS spectrophotometer. Results were expressed as mg cyanidin-3-glucoside equivalents per kg fresh fruit.

D. Microbial Analysis

Strawberry samples were weighed and placed in a stomacher bag with 100 mL PBS solution and shaken for 60 seconds. A 1 mL aliquot was mixed with 9 mL buffer solution and serial dilutions were prepared. Total aerobic bacterial count (TABC), total coliform count (TCC), and yeast and mold counts (YAMC) were determined by plating 0.1 mL diluted samples onto plate count agar (PCA; Difco Co., Detroit, MI), Violet Red bile agar (VRBA), and Dichloran rose Bengal chloramphenicol (DRBC) agar (Remel), respectively. PCA and VRBA plates were incubated at 37°C for 24–48 h and DRBC plates at 25°C for 4–5 days. Three replicates were carried out for each treatment and opening location. Results were expressed as log CFU g^{-1} (mean ± standard deviation).

E. Statistical Analysis

The effect of packaging material and opening location on weight loss, shelf life, aerobic microbial count, and physicochemical properties was analyzed using one-way ANOVA. All packaging treatments were compared with the control and with each other. A separate augmented factorial analysis (two-way ANOVA plus control) was carried out for each day of storage to compare treatments until appearance of grey mold. Multiple comparisons were carried out using Tukey's procedure. All statistical analyses were performed using GenStat (Twelfth Edition, Copyright 2009, VSN International Ltd).

Treatments were withdrawn upon first appearance of mold, so the data are progressively censored and the set of treatments contributing to the analysis is not constant across storage days. Each storage day was therefore analysed as an independent cross-section using only those treatments still present on that day, rather than as a repeated-measures analysis across the full 21-day period. Least significant difference (LSD) values are consequently specific to the treatments remaining on a given day and should not be used to compare across days or against treatments already withdrawn. No imputation was performed for withdrawn treatments, and mean separation letters within a row apply only to the treatments for which data are reported in that row.

Percent changes in total polyphenol and total monomeric anthocyanin content relative to day 0 were tested by one-way ANOVA with Tukey adjustment and are reported with the corresponding P values.

TABLE I. EFFECT OF PACKAGING MATERIAL AND OPENING LOCATION ON WEIGHT LOSS (G) AVERAGE OVER 21 DAYS OF STORAGE

Day	A1	A2	A3	B1	B2	B3	Control	LSD
2	0.658e	0.733de	0.866d	1.848b	1.607c	1.756bc	2.963a	0.182
3	1.361d	1.385d	1.613d	3.619b	3.142c	3.304c	4.608a	0.295
5	2.810b	2.608b	2.991b	7.200a	6.177a	6.288a	6.457a	1.377
7	4.214c	3.790d	4.054cd	10.858a	9.283b	9.273b	10.616a	0.408
10	5.530de	5.260e	5.820d	16.170a	14.070c	13.770c	14.610b	0.377
14	7.290c	6.680d	7.240c	22.330a	19.740b	19.410b	.	0.450
18	9.040c	8.560c	9.030c	28.380a	25.130b	24.940b	.	0.582
21	10.580b	10.270b	10.470b	33.410a	*	*	.	0.894

III. RESULTS

A. *Weight Loss and Shelf Life*

Packaging material and ventilation significantly affected UV-treated strawberry weight loss ($P \leq 0.05$). Styrofoam packaging had the least weight loss compared to molded pulp and control. After 21 days, Styrofoam accumulated approximately 11% weight loss relative to initial weight, while molded pulp lost approximately 32%. The control was removed after 11 days due to mold development. No significant effect of ventilation opening location on weight loss was detected.

1) A1: Styrofoam upper opening; A2: Styrofoam lateral opening; A3: Styrofoam lower opening; B1: Molded pulp upper opening; B2: Molded pulp lateral opening; B3: Molded pulp lower opening; Control: polyethylene clamshell. Within a row, means followed by different letters differ significantly ($P \leq 0.05$); mean separation applies only to the treatments reported in that row. An asterisk (*) indicates that visible mold was detected in that treatment on that day, after which the package was withdrawn and no further data were collected. A period (.) indicates that data collection had already ceased at an earlier time point because of total microbial spoilage: control packages developed mold on day 11 and were withdrawn, so no control data exist from day 14 onward. The LSD reported for day 21 was calculated only from the four treatments still present on that day (A1, A2, A3, B1); it excludes B2 and B3, which had spoiled, and the control, which had been withdrawn on day 11.

B. *Sensory Test Results*

No differences among treatments were detected on day 0 for any sensory measure. After 5 days, significant differences in fruit firmness were observed between Styrofoam and molded pulp treatments ($P < 0.001$), with Styrofoam best preserving firmness. The same pattern applied to color. Odor and palatability also differed significantly, with Styrofoam (upper opening) achieving the highest values, followed by lateral and lower, then control, then molded pulp. Overall acceptability at day 5 was highest for Styrofoam (upper opening).

At day 10, significant differences in firmness, color, and odor between Styrofoam and molded pulp were maintained ($P < 0.001$). The control was removed after day 11 due to mold. After day 15, significant differences in all sensory attributes were observed between Styrofoam (upper and lateral openings) versus Styrofoam (lower opening) and molded pulp ($P < 0.001$). The same pattern was maintained through day 21.

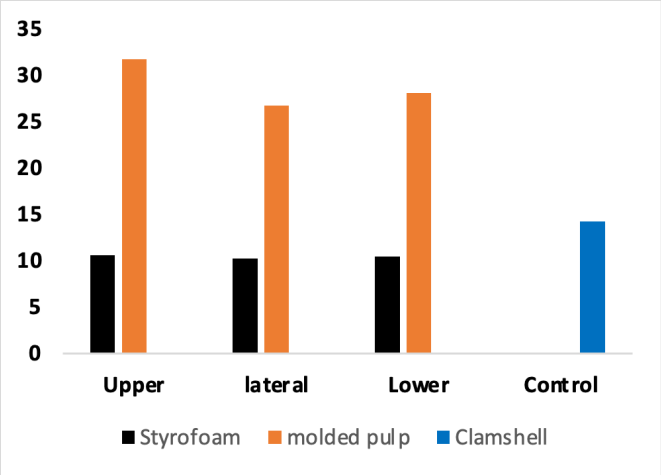


Fig. 1. Weight loss (%) of strawberries treated with UV light packaged in different packaging materials and opening locations. Error bars represent standard deviation (n = 3).

TABLE II. EFFECT OF TREATMENT ON SENSORY ATTRIBUTES (FIRMNESS, COLOR, ODOR, PALATABILITY, OVERALL ACCEPTABILITY) AT DAY 10

Treatment	Firmness	Color	Odor	Palatability	Overall Acc.
A1	7.33a	7.67a	7.50a	7.50a	7.33a
A2	7.33a	7.17a	6.67ab	7.17ab	7.17a
A3	6.83a	6.00b	6.00b	6.50b	6.33b
B1	4.00bc	3.17d	3.83cd	3.33d	3.33d
B2	3.33c	2.50d	3.00de	2.50e	2.67d
B3	3.67c	3.00d	2.83e	3.17de	3.00d
Control	4.83b	4.33c	4.17c	4.17c	4.67c
LSD	0.86	0.88	0.92	0.75	0.67

Sensory attributes were scored on a 9-point hedonic scale. Within a column, means followed by different letters differ significantly ($P < 0.05$).

C. *Total Polyphenol Content (TPC)*

At the beginning of storage, TPC was 230.25 ± 10.23 mg GAE per 100 g fresh weight. A significant 40% increase in TPC was observed on day 5 ($P < 0.001$), followed by a decline on day 10 ($P < 0.001$). UV exposure has been

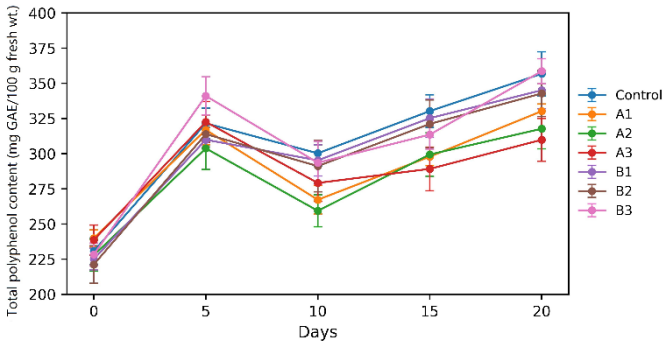


Fig. 2. Total polyphenol content (mg GAE per 100 g) of strawberries stored in different packaging materials and opening locations. Error bars represent standard error (n = 3).

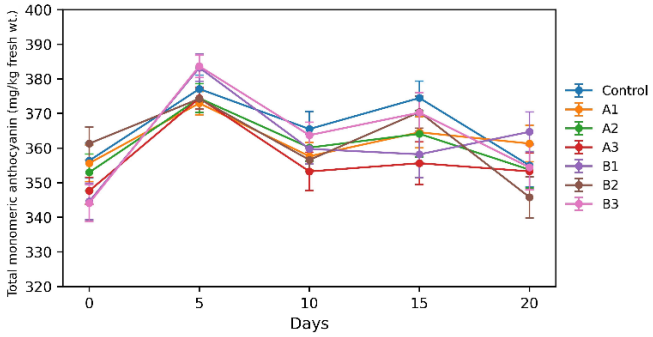


Fig. 3. Total monomeric anthocyanin content (mg/kg) of strawberries stored in different packaging materials and opening locations. Error bars represent standard error (n = 3).

shown to increase the expression of genes involved in the phenylpropanoid pathway, such as phenylalanine ammonia-lyase [10]. No significant effect of packaging type or ventilation placement on TPC was observed until day 10. On days 15 and 20, egg-crate-packaged strawberries had significantly lower TPC ($P < 0.05$), likely associated with reduced fungal growth in egg-crate packaging, as higher fungal growth can result in polyphenol accumulation [11].

D. Total Monomeric Anthocyanin (TMA) Content

At the start of storage, total anthocyanin content was 351.81 ± 6.53 mg/kg fresh weight. A 7% increase in anthocyanin levels was observed by day 5 ($P < 0.001$), consistent with UV-induced activation of the phenylpropanoid pathway [12]. Throughout the storage period, there was no statistically significant effect of packaging type or ventilation placement on anthocyanin content, suggesting anthocyanins remained relatively stable across different storage conditions.

E. Aerobic Microbial Count, Total Yeast and Mold, and Total Coliform Count

The microbial count on Day 0 (before packaging) was 9.86 ± 0.086, 5.89 ± 0.099, and 6.99 ± 0.085 log CFU/g for TABC, TCC, and YAMC, respectively. The strawberries were visually sound, with no visible signs of spoilage at the time of analysis. However, the relatively high initial aerobic bacterial count may be attributed to the natural surface microbiota present on strawberries, the time elapsed between harvest

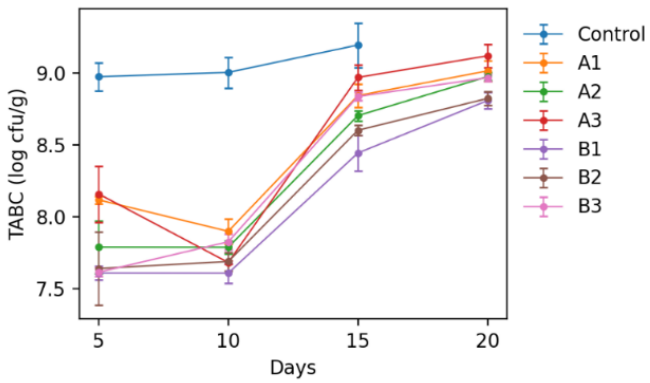


Fig. 4. Total aerobic bacterial count (log CFU/g) of UV-C-treated strawberries stored in different packaging materials and opening locations. Error bars represent standard deviation.

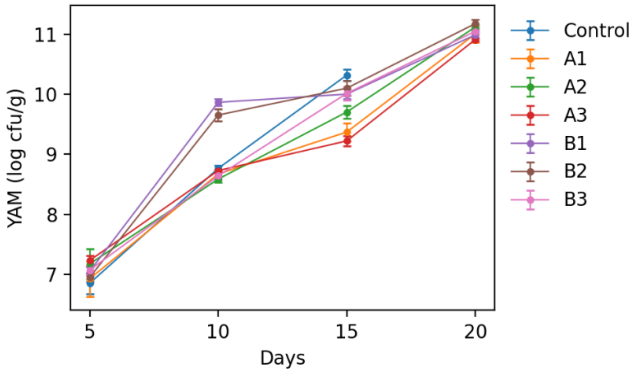


Fig. 5. Total yeast and mold count (log CFU/g) of UV-C-treated strawberries stored in different packaging materials and opening locations. Error bars represent standard deviation.

and analysis, and normal variability associated with sample handling, preparation, and microbiological enumeration.

After UV-C treatment, the average TABC, TCC, and YAMC on Day 0 were 9.13 ± 0.100, 5.64 ± 0.114, and 5.416 ± 0.106 log CFU/g, respectively. Control strawberries developed mold by day 11 and were withdrawn at that point. Styrofoam packages remained free of visible mold through day 21, when the trial was terminated. Among molded pulp packages, the lateral and lower opening treatments (B2, B3) developed mold by day 21, while the upper opening treatment (B1) remained mold-free to the end of the trial.

Packaging material significantly affected TABC, YAMC, and TCC during storage ($P < 0.05$). TABC and YAMC increased progressively over the storage period, while TCC decreased and became undetectable by Day 20. Strawberries stored in clamshell (control) had higher bacterial counts compared to alternative packaging. Foam egg crates demonstrated lower yeast and mold counts while molded pulp showed lower coliform counts compared to clamshell. The reduced microbial growth in new packaging materials can be attributed to their absorptive capacity, which may help regulate moisture levels and create an environment less favorable for microbial proliferation [13, 14].

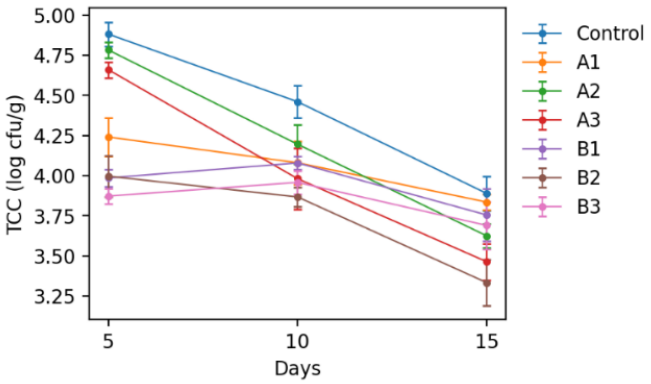


Fig. 6. Total coliform count (log CFU/g) of UV-C-treated strawberries stored in different packaging materials and opening locations. Error bars represent standard deviation.

IV. Discussion

The results showed that packing strawberries in Styrofoam egg-crate containers increased the storage period up to 21 days with the least weight loss and microbial count. UV-C applications on fresh fruits and vegetables have shown a promising approach for post-harvest treatment, as UV-C delays ripening and preserves the firmness of fruit cell walls by affecting hydrolyzing enzymes such as pectin esterase and 1,4-β-D-glucanase, leading to less cell wall degradation.

Placing these results alongside earlier UV-C studies suggests that the magnitude of the reported benefit depends less on whether UV-C is applied than on the storage conditions into which the treated fruit is placed. The extension observed here exceeds the roughly 9-day extension reported by Idzwana et al. [15] and the improvements reported by Nigro et al. [16], both of which applied UV-C without a modified package. Conversely, Armenteros et al. [17] and Pinheiro et al. [18] recorded proportionally larger benefits at storage temperatures of 12–24 °C than we observed relative to our 4 °C control. This pattern is consistent with UV-C-mediated reductions in microbial load mattering most where the surviving population is growing quickly; at 4 °C, low temperature already suppresses growth, so the incremental contribution of irradiation is compressed and differences attributable to the package become comparatively more visible.

The apparent divergence from Sola et al. [19], who found UV-C least effective under dry conditions similar to ours, is best read as a difference in what was being compared rather than as a contradiction. Sola et al. isolated irradiation against an un-irradiated control under otherwise identical packaging, whereas every treatment in the present study received the same UV-C dose and differed only in tray material and ventilation. Our comparison is therefore between packages within a uniformly irradiated system and can neither confirm nor refute their finding on irradiation efficacy. A further plausible contributor is surface moisture at the moment of exposure: condensate films on chilled fruit shield adhering microorganisms from 254 nm radiation, so nominally equal intensities can deliver unequal effective doses depending on how fruit is handled between cold storage and the UV tunnel. Reported intensity alone is thus a poor basis for comparison across studies, and future work should report delivered dose (mJ/cm²), exposure geometry, and fruit surface condition.

The changes in TPC during storage indicate a dynamic response to storage conditions. The observed reduction in TPC in egg-crate-packaged strawberries is consistent with the concurrent decrease in yeast and mold counts. Lower fungal growth may limit stress-induced polyphenol biosynthesis, as pathogens can stimulate plant defense mechanisms involving phenolic compounds [11]. In contrast, total anthocyanin content remained stable across storage conditions. The initial 7% increase in anthocyanin levels is consistent with UV-induced activation of the phenylpropanoid pathway [12]. Anthocyanin stability suggests these pigments require fewer storage interventions than total polyphenols.

Both alternative packaging materials (foam egg crate and molded pulp) significantly reduced TABC, YAMC, and TCC compared to the control during storage. Molded pulp, particularly with side and bottom holes, demonstrated enhanced barrier properties that minimize oxygen transmission and inhibit bacterial growth [14]. While foam egg crates showed some effectiveness in reducing yeast and mold growth on day 15, this difference was not significant on day 20, indicating that the effect may be transient. Overall, alternative packaging materials provide better microbial control compared to clamshell packaging, suggesting these materials may create a more favorable storage environment [13].

A. Limitations

The principal limitation of this study is that UV-C treatment was applied uniformly across all packaging treatments, with no un-irradiated counterpart of either egg-crate material. The design therefore contains no factorial contrast between irradiation and packaging, and the 21-day shelf life observed for Styrofoam trays cannot be partitioned between the two. At least three mechanisms are consistent with the data and cannot be separated by the present design: direct reduction of surface microbial load by UV-C; passive moisture and gas management by the tray material; and reduced mechanical bruising from the cushioned egg-crate geometry, which limits the wound sites through which Botrytis cinerea establishes. The weight-loss data are the most informative on this point, since all six egg-crate treatments received an identical dose yet differed markedly from one another, indicating that a substantial share of the observed effect is attributable to the package rather than to irradiation. The results should accordingly be read as a comparison of packaging systems under UV-C treatment, and the language of a combined effect should be understood as descriptive of the treatment applied rather than as a demonstration of synergy. A full factorial design including un-irradiated Styrofoam, molded pulp, and clamshell arms is required to resolve this and is the logical next step.

Three further constraints bound the generality of these findings. First, the study used a single cultivar (Chandler) from a single harvest at one farm, so cultivar-dependent differences in cuticle thickness, initial microbial load, and phenolic composition are not captured, and between-harvest variability is unmeasured. Second, a single UV-C intensity of 964 µW/cm² was applied, so no dose-response relationship

can be inferred, and it is not known whether the observed effects would persist, increase, or reverse at other doses; higher doses are known to induce surface damage in soft fruit. Third, shelf life was defined by first appearance of visible mold, an endpoint that is conservative from a food-safety standpoint but does not correspond to the point of consumer rejection; several treatments fell below the mid-point of the sensory scale well before mold appeared, so the commercially useful shelf life is shorter than the mold-free interval reported here.

Because packaging systems differ visibly by design, panelists cannot be blinded to treatment in any packaging comparison; this is inherent to the study type rather than a specific limitation of this work. The study's primary conclusions rest on the instrumental weight-loss and microbial measures, with hedonic scores reported as supporting evidence.

V. Conclusions

Among UV-C-treated packages, Styrofoam egg-crate trays maintained mold-free fruit through day 21, compared with 11 days for the clamshell control, and both alternative materials reduced total aerobic bacterial count, yeast and mold count, and coliform count relative to clamshell. Because irradiation was applied uniformly, these differences are attributable to the packaging systems compared within a UV-C-treated environment and do not by themselves establish the contribution of UV-C.

Total polyphenol content exhibited dynamic fluctuations influenced by storage conditions, with egg-crate-packaged strawberries showing significantly lower TPC during the final storage stage, likely due to reduced fungal growth and associated stress-induced polyphenol biosynthesis. Anthocyanin content remained stable across packaging conditions throughout the study. Ventilation location did not significantly affect any measured attribute between treatments.

These findings indicate that tray material and geometry are meaningful determinants of strawberry shelf life within a UV-C-treated post-harvest system. The immediate priority for future work is a factorial design incorporating un-irradiated counterparts of each packaging type, which would allow the contributions of irradiation and packaging to be separated and would test whether the two act additively or synergistically. Subsequent work should extend across cultivars, harvests, and UV-C doses, and should evaluate biodegradable alternatives that reproduce the cushioning and moisture-retention behavior of Styrofoam without its environmental cost.

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