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ORIGINAL ARTICLE

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Curcumin-mediated photodynamic treatment to extend the postharvest shelf-life of strawberries

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Abstract

This study investigated the potential use of curcumin-mediated photodynamic treatment as a postharvest decontamination technique to reduce microbial load and growth and therefore extend the shelf life of strawberries. Curcumin was applied on strawberries, followed by illumination and storage at 4°C for 16 days. Strawberries were evaluated for decay, microbial load, and physicochemical properties such as weight loss, color, and firmness during storage. The findings revealed that curcumin-mediated photodynamic treatment effectively reduced the decay incidence and severity in strawberries, with 20% less decay occurrence compared to untreated fruits, which was shown to be dependent on curcumin concentration. While a complete reduction in microbial load was observed upon treatment, microbial growth remained unaffected throughout storage. Moreover, photodynamic treatment did not show any adverse impact on color properties and firmness of strawberries. This eco-friendly technique presents potential for fruit's shelf-life extension, although optimization of treatment parameters and photodynamic unit design seems to be essential.

KEYWORDS
curcumin, decay incidence, photodynamic treatment, postharvest decontamination, strawberry

1 | INTRODUCTION

Strawberries (*Fragaria* × *ananassa* Duch) belong to the Rosaceae family and are widely consumed, contributing to a global industry value of approximately US$17 billion (FAOSTAT, 2020). However, their short shelf life poses challenges due to water loss and mechanical damage throughout the production and retail process. Additionally, the plant pathogen, *Botrytis cinerea*, causes gray mold that is the main postharvest spoilage and results in significant economic losses for the strawberry industry. Conventional methods to control *B. cinerea* involve using commercial fungicides, but the emergence of fungicide-resistant strains has reduced their effectiveness. Therefore, various non-thermal preservation techniques such as gamma irradiation (Shankar et al., 2021), essential

oil–enriched edible coatings (Martínez et al., 2018), cold plasma (Rana et al., 2020), and ozone (Contigiani et al., 2018) have been increasingly explored to extend the shelf life of strawberries. These methods provide a significant advantage in inactivating microorganisms and enzymes and maintaining quality while operating at low temperatures. Although some non-thermal processing techniques may generate heat due to internal energy reaching to 40°C, such as adiabatic heating during high hydrostatic pressure processing, they are considered non-thermal because they do not rely on high temperatures to inactivate the microorganisms. This helps prevent the harmful effects of heat on sensorial and nutritional value of foods (Pereira & Vicente, 2010). These techniques are, however, limited by their cost and potential consumer reluctance, driven by concerns over health safety and changes in sensory attributes.

An alternative approach showing promise is photodynamic treatment, which exhibits antimicrobial effects against a broad spectrum of microorganisms, including molds (Al-Asmari et al., 2017; Ambrosini et al., 2020; Conrado et al., 2021; Gonzales et al., 2017; Song et al., 2020). Photodynamic treatment is a non-thermal technique, and its principle of action involves the photosensitizer being excited by a specific wavelength of light. The photosensitizer then enters a single state and can transition to a triplet state, which follows two photochemical pathways (Type I and II) to react with oxygen and generate reactive oxygen species (ROS) (Kwiatkowski et al., 2018). Therefore, this technique harnesses the generated ROS to induce oxidative damage in different cellular structures of microorganisms such as proteins, lipid membranes, and nucleic acids, leading to cell death, which in turn reduces the risk of resistance development (Mannozzi et al., 2018). The antimicrobial ability of this technique using different photosensitizers has been studied on various foods such as orange juice (Bhavya & Hebbar, 2019), fresh-cut pineapple (Bhavya et al., 2021), apple juice (Lee et al., 2023), and kiwifruit (Long et al., 2024). Curcumin, a natural pigment derived from *Curcuma longa* L. plant tubes, possesses multiple biological activities such as antioxidant (Alavi et al., 2018), anticancer (Shehzad et al., 2013), and antimicrobial (Moghadamtousi et al., 2014) properties. It serves as a natural photosensitizer, responsive to blue light in the range of 410–430 nm (Penha et al., 2017). Research indicates the effective photodynamic antimicrobial capacity of curcumin against various microorganisms, such as 96% reduction in *B. cinerea* spore germination (Wei et al., 2021), substantial reductions over 3 and 2 log colony-forming units (CFU) g^{-1} in *Escherichia coli* and *Staphylococcus aureus* (Correa et al., 2020), and successful control of pathogens on various fresh-cut fruits (Chai et al., 2021; Wang et al., 2023; Zou et al., 2021), without compromising product quality during storage.

The aim of this study was to evaluate the potential use of curcumin-mediated photodynamic treatment as a postharvest solution for strawberries. This involved applying a curcumin solution onto the strawberries' surface and illuminating them under optimal conditions, as determined in our previous study (Seididamyeh et al., 2023). Two experiments were conducted using freshly harvested strawberries. Following curcumin application and photodynamic treatment, the strawberries were stored at 4°C and assessed for microbial counts and physicochemical attributes, including color, firmness, decay, total soluble solids (TSSs), and titratable acidity (TA).

2 | MATERIALS AND METHODS

2.1 | Fruit samples

Two different experiments were carried out, and strawberries were procured directly from farms (QLD, Australia). The specific geographical information regarding the farm origins of the strawberries is present in Table 1. The sorting process involved picking healthy fruits devoid of fungal infections and physical blemishes, ensuring uniformity in color and size.

2.2 | Light source and photosensitizer

The illumination of strawberries was performed in a light impenetrable chamber equipped with light-emitting diodes (LEDs; 420 nm, 100–240 V; HYG05-4*200W-W, COB LED Light Fixture, China) positioned both above and below the fruits. To prevent potential temperature elevation, heat sink and cooling fan systems were incorporated within the chamber. The photosynthetic photon flux density (μmol m^{-2} s^{-1}) of LEDs was measured using a spectrometer (HR-450, HiPoint) at 10 different locations with 10-cm distance from the light source and was converted into light irradiance (mW cm^{-2}) (Roh et al., 2016).

A stock solution of curcumin (from *Curcuma longa*, ≥65%, Sigma-Aldrich) was prepared (400 μmol L^{-1}; w/v) in ethanol (99.8%, Fisher Chemical) and stored at −20°C for 1 week. The stock solution was diluted with ultrapure water (Milli-Q, Millipore, Biopak Polisher) to obtain working concentrations of 13 and 32.5 μmol L^{-1} (5% (v/v) ethanolic curcumin in water) for the first and second experiments, respectively. The curcumin concentrations were determined based on the optimal conditions obtained in our previous study (Seididamyeh et al., 2023). The working solutions were prepared on the day of treatment.

TABLE 1 Geographical details of the strawberry farms in Queensland, Australia.

Experiment	Variety	Location	Harvest date	Farm	Latitude	Longitude
1	Red Rhapsody	Bundaberg	October 21, 2020	Winter strawberries	S24°58′9.6359″	E152°25′15.0876″
2	Cabrillo	Stanthorpe	November 16, 2020	Ashbern farms	S28°39′22.8024″	E151°56′15.7452″

Source: https://www.findlatitudeandlongitude.com (2021).

2.3 | Photodynamic treatment

In the two experiments, four groups were established: untreated (control), light-treated (in the absence of curcumin; light control), curcumin-treated (in the absence of light; curcumin control), and photosensitized (light treated in the presence of curcumin). The application of curcumin working solution was carried out using an air spray gun (AirPro K15A, Garco), followed by illumination at 317.53 W m^{-2} for 10 min (equivalent to light dose of 19.05 J cm^{-2}). This causes an increase in temperature of strawberry surface to 30°C. Due to the static nature of LED unit employed in this study, the strawberries were flipped after 5 min of illumination to ensure uniform exposure on both sides. Subsequently, the strawberries were air-dried for 15 min at room temperature using a fan. The strawberries in first and second experiments were respectively packed in oriented polystyrene and polyethylene terephthalate containers (iKon Pack) with ventilated lids and sanitized with 70% ethanol. Each package contained five randomly selected strawberries, constituting one replicate. These packed strawberries were stored at 4°C and 90 ± 3% relative humidity (RH) for 15 days in the first experiment and 16 days in the second experiment. On each sampling day, six packages from each treatment were randomly selected for destructive measurements. Moreover, two sets of strawberries, each with eight packages per treatment, were stored under similar conditions: one set for color measurement and the other for weight loss and visual observation during storage.

2.4 | Microbiological analysis

The microbial load of strawberries was assessed in terms of total plate count (representing total aerobic count), as well as yeasts and molds count. Ten grams of samples were aseptically collected from the strawberry surface using sterilized scalpels and forceps. Then, 90 g of tryptone water (0.1% w/v; LP0042, Oxoid) were added in the sampling bag and homogenized for 1 min in a stomacher (BA6021, A.J. Seward & Company Limited). The resulting suspension was 10-fold diluted and pour plated (1 mL) using plate count agar (PCA; Oxoid) or spread plated (0.1 mL) onto Dichloran Rose Bengal Chloramphenicol (DRBC; CM0727, Oxoid) agar. Duplicate plates were prepared for each dilution. The PCA and DRBC plates were incubated at 30°C and 25°C, respectively, for 72 h. Subsequently, the population of aerobic bacteria, yeasts, and molds were quantified as CFU using a colony counter (Stuart Scientific) and reported as $\log_{10}$ (CFU g^{-1}). The analysis involved three replications, with each replication being a composite of samples taken randomly from two packages. There were six packages as six replications for each sampling day and each treatment.

2.5 | Decay incidence

Visual assessments were conducted by three assessors on each sampling day to identify any visible signs of decay, including the occurrence of gray mould infection and brown spots on the strawberries. Decay percentage was calculated using Equation (1):

$$\text{Decay}\ \ (\%) = \frac{\text{The number of decayed fruits}}{\text{The total number of fruits}} \times 100 \quad (1)$$

Assessors also assigned ratings to the fruits for decay (Figure S1) on a scale of 0 (lowest) to 10 (highest).

2.6 | Physicochemical analysis

2.6.1 | Weight loss

Changes in weight were measured using a precise analytical balance (± 0.01; PB3002-S, Mettler Toledo). Weight loss was calculated using Equation (2):

$$\text{Weight loss}\ \ (\%) = \frac{W_0 - W_t}{W_0} \times 100 \quad (2)$$

where W_0 is the initial weight and W_t is the weight at specific time intervals.

2.6.2 | Color

The surface color of strawberries was assessed using a chromameter (CR-400, Konica Minolta Sensing Inc.) by taking three readings on each strawberry. The results were expressed as L^* (white [100] to black [0]), a^* (green [−] to red [+]), b^* (blue [−] to yellow [+]). The chroma (C) and hue angle (H) values were derived using the following equations (Ohta, 1977):

$$C = \sqrt{\left(a^{*2} + b^{*2}\right)} \quad (3)$$

$$H = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (4)$$

2.6.3 | Firmness

The firmness of strawberries was assessed using a Texture Analyzer (TA1, Lloyd Materials Testing, Ametek Inc.). A cylindrical stainless steel flat probe with a diameter of 6 mm was used to penetrate the equatorial zone of the fruit to a depth of 7 mm at a speed of 0.5 mm s^{-1}. The highest penetration force was recorded as the firmness value (N). In the first trial, each fruit was halved, and both halves were measured. In the second trial, two measurements were taken on a whole fruit. The experiment was performed on 10 fruits per treatment on each sampling day.

2.6.4 | Total soluble solids, pH, and titratable acidity

At each storage interval, three strawberries per treatment were homogenized in a ball mill (MM400, Retsch) for 20 s at 30 s^{-1} and considered as one replicate. About 2 g of the puree was then centrifuged (16,000 rcf, 5 min, 25°C; 5415D, Eppendorf) and the TSS of the supernatant was measured using a refractometer (PAL-1, Atago) and expressed in percentage (AOAC 932.12; AOAC, 1995).

Ten grams (m) of the puree were diluted with 100 mL of distilled water, and the pH was measured using a pH meter (632 pH-meter, Metrohm). The diluted samples were subsequently titrated using an auto-titrator (765 Dosimat, Metrohm) with 0.1 N NaOH (Chem Supply) to adjust the pH to 8.2 (AOAC 942.15; AOAC, 1995). TA was expressed as % citric acid and calculated as follows:

$$\text{TA}\ (\%) = \frac{V_{\text{NaOH}} \times 0.1 \times 0.064}{m} \times 100 \quad (5)$$

2.7 | Statistical analysis

The results were analyzed by one-way analysis of variance (IBM SPSS 27, SPSS Inc.) and Tukey's tests. Significance was determined at $p < 0.05$. All experiments were performed at room temperature, and data were collected from at least three replications.

3 | RESULTS AND DISCUSSION

3.1 | Impact of photodynamic treatment on strawberries

The optimized in vitro conditions for photodynamic treatment (Seididamyeh et al., 2023), using 13 μmol L^{-1} curcumin, were applied to fresh "Red Rhapsody" strawberries in the first experiment. The results revealed that the optimized in vitro condition was unable to effectively delay microbial growth and visible fungal infections in the treated strawberries (Figures 1 and 2). Consequently, a higher curcumin concentration (32.5 μmol L^{-1}) under similar illumination conditions was employed for the second experiment ("Cabrillo" strawberries), according to the observed dependency on curcumin concentration in the in vitro experiments (Seididamyeh et al., 2023).

3.2 | Decay incidence and severity

Strawberry shelf life is usually determined by the emergence of fungal growth on the fruit. Therefore, untreated and treated strawberries were visually evaluated for any indications of fungal growth during storage. Photodynamic-treated strawberries (both "Red Rhapsody" and "Cabrillo") showed lower decay levels up to days 5 and 10 of storage, respectively, in comparison to untreated fruits (Figure 1a,b). Results indicated that while photodynamic treatment failed to delay fungal spoilage, it did slightly mitigate the severity of decay in "Cabrillo" strawberries (Figure 1d). This observation underscores that photodynamic treatment exhibited a marginal reduction in the severity of fungal infection in strawberry fruits. However, further studies are needed to optimize the conditions for strawberry photo-decontamination. Peretto and colleagues demonstrated a 57% reduction in decay using edible films containing carvacrol and methyl cinnamate in strawberries, stored at 10°C for 10 days. This was attributed to the antifungal activity of these two active components and their slow release during storage (Peretto et al., 2014). Similarly, Duarte-Molina and team reported a 16%–42% reduction in fungal decay in strawberries

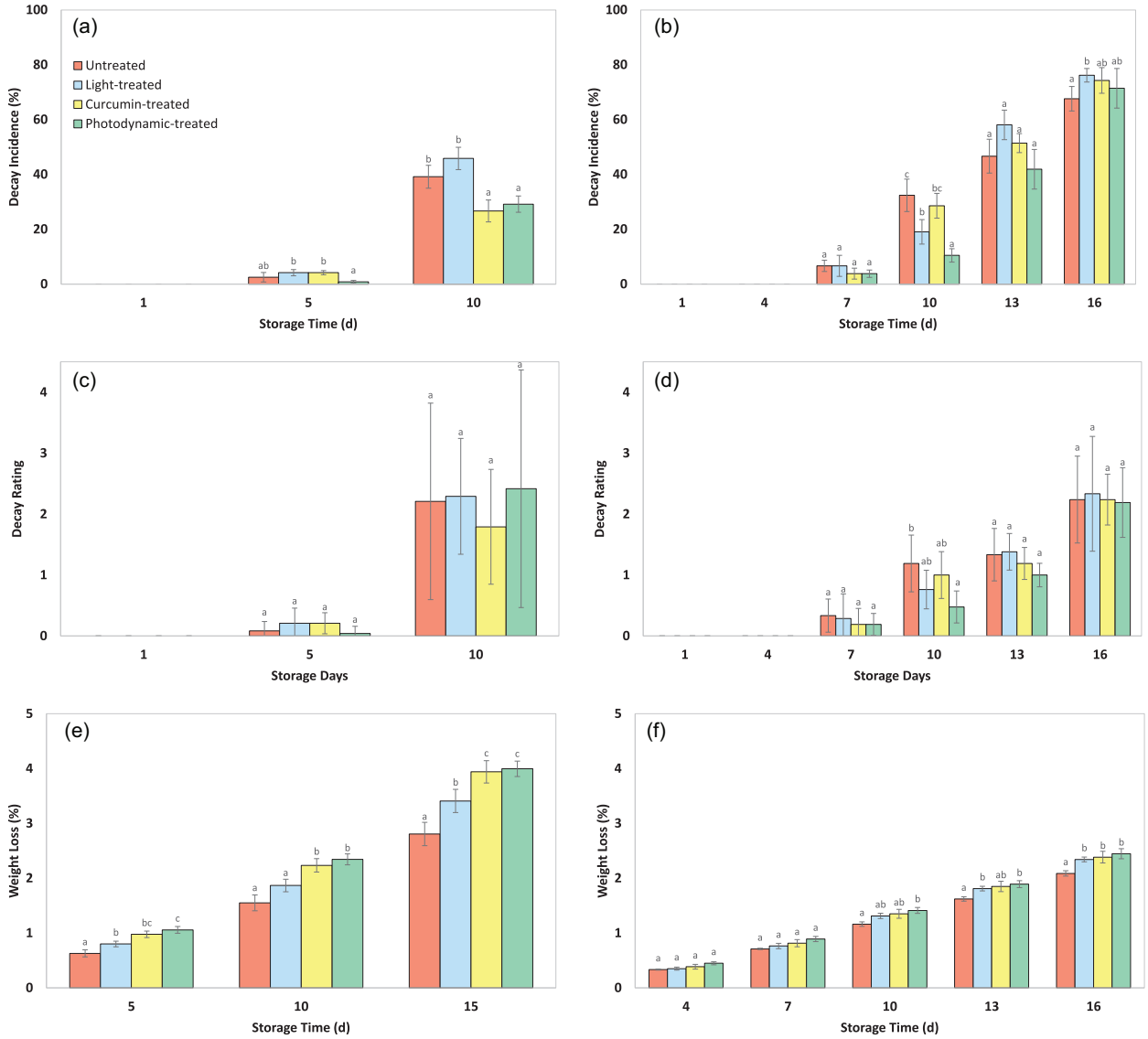

FIGURE 1 Effect of curcumin-mediated photodynamic treatment on decay incidence, decay rating, and weight loss of "Red Rhapsody" (a, c, and e) and "Cabrillo" (b, d, and f) strawberries during 15- or 16-day storage at 4°C. Error bars indicate the standard deviation of eight replicates; different letters show a significant ($p < 0.05$) difference among treatments on each storage time. There were three assessors evaluating the decay rating, and as the variation between individuals was high, statistical differences were not done for graphs c and d.

treated with pulsed light, compared to untreated fruits stored at 6°C for 8 days (Duarte-Molina et al., 2016). This observation may be due to the generation of ROS through endogenous photosensitizers within microorganisms, along with oxidative stress enhancing phenolic content, which subsequently influences decay incidence.

3.3 | Microbial load

The most substantial post-harvest challenge confronting the strawberry industry is the proliferation of bacteria and fungi, which is influenced by a nutritious environment and an increased level of sugar at the time of harvest. Figure 2 shows the changes in microbial load for "Red Rhapsody" and "Cabrillo" strawberries during storage. Notably, both untreated and treated strawberries exhibited an increase in microbial load during storage in both experiments. In "Red Rhapsody" strawberries, a complete reduction was noted in aerobic plate and yeast counts after photodynamic treatment (Figure 2a,c), which was lower than detection limit (<10 CFU g^{-1}). During storage, the yeasts count in photodynamic-treated "Red Rhapsody" strawberries remained lower than the untreated ones, reaching 2.02 and 3.04 $\log_{10}$ (CFU g^{-1}), respectively, on day 15. No significant difference in aerobic plate and mould

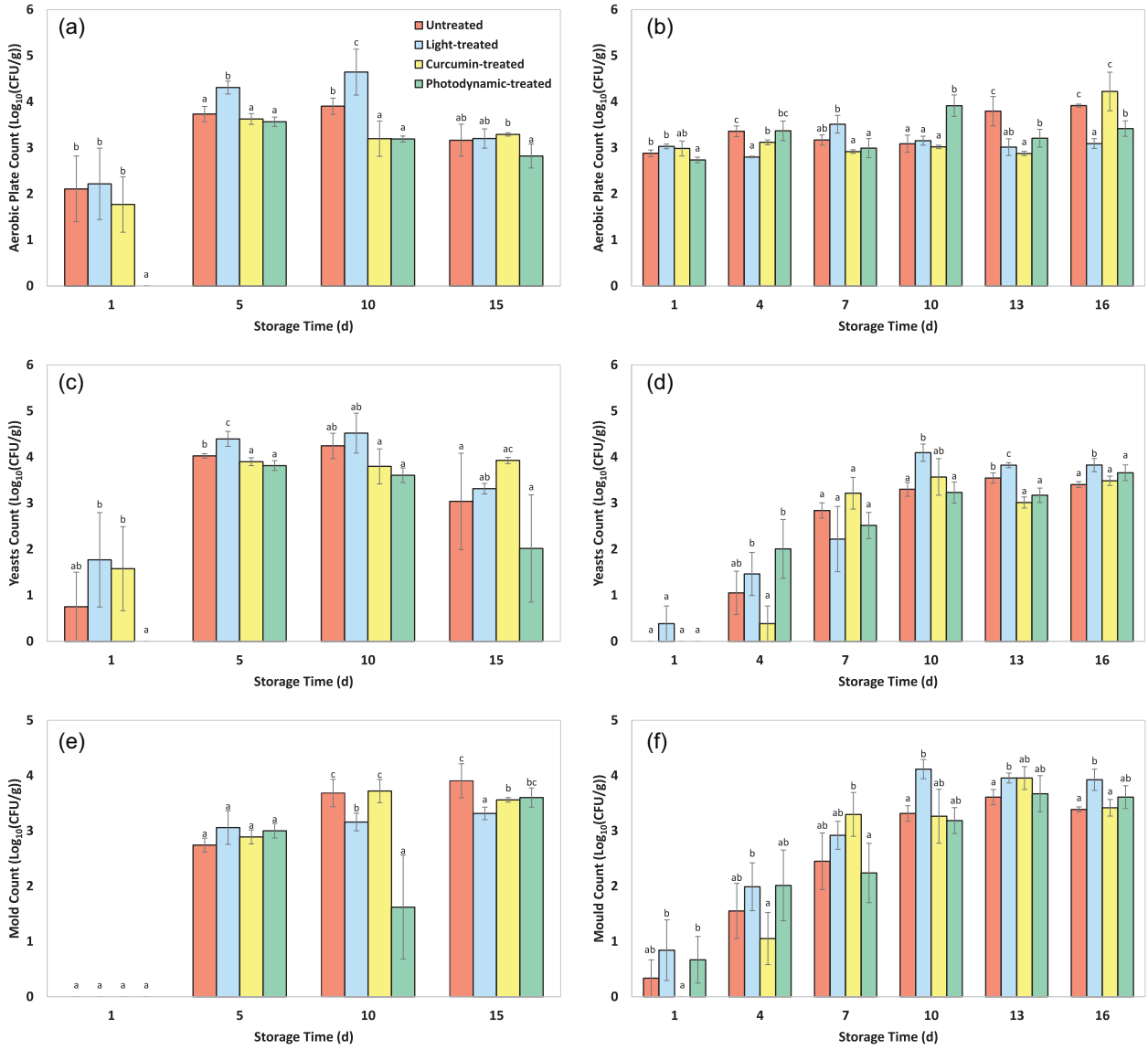

FIGURE 2 Effect of curcumin-mediated photodynamic treatment on aerobic plate, yeasts, and mold counts of "Red Rhapsody" (a, c, and e) and "Cabrillo" strawberries (b, d, and f) during storage at 4°C (90% relative humidity [RH]) for 15 or 16 days. Error bars indicate the standard deviation of three replicates; different letters show a significant ($p < 0.05$) difference among treatments on each storage time. CFU, colony-forming units.

counts were observed between untreated and treated "Red Rhapsody" strawberries during storage (Figure 2a,e). The mould count in "Red Rhapsody" strawberries increased to 2.93 $\log_{10}$ (CFU g^{-1}) in untreated and to 2.70 $\log_{10}$ (CFU g^{-1}) in photodynamic-treated fruits by day 15. In terms of "Cabrillo" strawberries, slightly lower aerobic plate counts were observed for photodynamic-treated strawberries compared to untreated ones (2.74 and 2.88 $\log_{10}$ [CFU g^{-1}], respectively) after the treatment, which was also found on days 7, 13, and 16 of storage (Figure 2b). In general, photodynamic treatment did not significantly affect the aerobic plate, yeasts, and molds counts of "Cabrillo" strawberries over the 16-day storage period, compared to the untreated fruits (Figure 2b,d,e).

Overall, the microbial results indicated that curcumin-mediated photodynamic treatment displayed inefficiency in reducing bacterial and mould load on "Cabrillo" strawberries. This could potentially be related to the static condition of the LED unit used, leading to uneven illumination across the fruit surfaces. The lower antimicrobial effect observed on "Cabrillo" strawberries may also be attributed to the higher concentration of curcumin and its low water solubility. This can lead to the aggregation of curcumin molecules, potentially impeding their accessi-

bility to microorganisms and reducing the antimicrobial photodynamic effect. Furthermore, our results showed that the growth of microorganisms was inhibited on day 1 and continued to grow during the storage time. This may be explained by the concentrations of curcumin used in this study that could impart a sub-lethal effect on the microorganisms due to not being able to generate sufficient amount of ROS to promote inactivation of microorganisms. Therefore, further studies are required to optimize the treatment factors for an efficient antimicrobial effect on fruits and understand the inhibitory or inactivating effect of photo-decontamination treatment on strawberry microflora. Nevertheless, our findings on "Red Rhapsody" strawberries are in agreement with those reported in literature, which documented significant microbial reduction upon photodynamic treatment. For instance, De Oliveira and colleagues demonstrated that the combination of 10 μg mL^{-1} acidified curcumin with UV-A lights (320–400 nm) led to a significant decrease in *Escherichia coli* O157:H7 and *Listeria innocua* populations inoculated on lettuce, spinach, and tomatoes by ca. 2 $\log_{10}$ CFU g^{-1} (de Oliveira et al., 2018). Similarly, Hyun and colleagues achieved over 1 log reduction in *E. coli* O157:H7 population inoculated on cherry tomatoes using 0.2 mmol L^{-1} curcumin and 5-day illumination with blue LED lights (460–470 nm) (Hyun et al., 2022). Another study reported complete inhibition of fungal lesion expansion in apples inoculated with *B. cinerea* spores and treated with 0.5 mmol L^{-1} curcumin and 15 min LED (420 nm) illumination (Wei et al., 2021). Notably, these studies generally focused on single microorganism inoculation and the antimicrobial photodynamic effect on the day of treatment only. However, our study considered the fruit's natural microflora acquired from farm and handling processes, and the antimicrobial effect on the treatment day as well as during the storage period. Our findings indicated that while there was almost no significant difference observed between the photodynamic-treated and untreated strawberries, the incidence of decay was lower in the photodynamic-treated fruits. This suggests that photodynamic treatment contributed to a reduction in the population of spoilage microorganisms. This effect may be attributed to the accumulation of phenolic compounds resulting from oxidative stress induced by light exposure, thus influencing microbial spoilage on fruits. Tao and colleagues observed an increase in total phenolic content and antioxidant activity in fresh-cut apples following photodynamic treatment. Additionally, a reduction in defense enzymes such as polyphenol oxidase and peroxidase in fresh-cut apples after photodynamic treatment was observed, resulting in lower oxidation of phenolic compounds and therefore an increase in their content (Tao et al., 2019). Hence, further studies are needed to elucidate the influence of process factors on decontamination efficacy in fruit with its inherent microflora acquired from farm and handling through harvest. Moreover, the intricate and uneven surface characteristics of strawberries cause difficulties for homogeneous exposure to photosensitizer and illumination that consequently affects the treatment efficacy.

3.4 | Firmness

Firmness is a critical determinant of fruit quality during its shelf life. It was shown that photodynamic treatment did not affect the firmness of "Red Rhapsody" (Table 2) and "Cabrillo" (Table 3) strawberries during storage. Fruit softening, typically associated with post-harvest storage, is largely driven by ripening. This can be enhanced by irradiation treatments that may activate pectolytic enzymes leading to cell wall solubilization (Ayala-Zavala et al., 2004). Our findings indicated that photodynamic treatment did not negatively affect the firmness of strawberries. However, light-treated and photodynamic-treated "Red Rhapsody" and "Cabrillo" strawberries displayed an increase in firmness during storage (Tables 2 and 3). This could be related to their distinct maturity stage and responses to light exposure. Furthermore, the firmness values could be influenced by factors such as dehydration and fruit shrinkage, which can cause a higher force to puncture the fruit.

3.5 | Weight loss

A significant factor affecting the quality of fresh fruits during storage is the occurrence of physiological weight loss. This is primarily caused by respiration and moisture evaporation from the surface of fruits. This natural weight loss leads to dehydration, shrinkage, and ultimately a decline in quality. Therefore, the impact of curcumin-mediated photodynamic treatment on the weight loss of fresh strawberries was evaluated. Figure 1e,f illustrates the changes in weight for both untreated and treated strawberries. Regardless of the applied treatment, a significant increase in weight loss was observed during storage. The rate of weight loss in "Cabrillo" strawberries showed slight differences between the applied treatments over 7 days of storage (Figure 1f). However, in both cultivars, "Red Rhapsody" and "Cabrillo," the weight loss was higher in curcumin-treated, light-treated, and photodynamic-treated strawberries compared to untreated fruits. This disparity in weight loss, occurring from storage day 5–15 for "Red Rhapsody" and storage day 7–16 for "Cabrillo" (Figure 1e,f), is attributed to the metabolic activity induced by light in the photodynamic-treated strawberries. This

TABLE 2 Effect of curcumin-mediated photodynamic treatment on firmness, pH, titratable acidity (TA), and total soluble solids (TSS) in "Red Rhapsody" strawberries during 15-day of storage at 4°C.

		Storage time (day)			
	Treatment	1	5	10	15
Firmness (N)	Untreated	4.40 ± 1.26^{ab}	4.12 ± 1.23^{a}	4.68 ± 1.35^{a}	nd
	Light treated	3.26 ± 0.87^{a}	4.82 ± 0.98^{a}	4.96 ± 2.91^{a}	nd
	Curcumin treated	4.60 ± 2.25^{b}	4.33 ± 1.20^{a}	5.32 ± 1.40^{a}	nd
	Photodynamic treated	4.18 ± 1.48^{ab}	4.31 ± 1.32^{a}	5.60 ± 1.49^{a}	nd
pH	Untreated	3.79 ± 0.02^{b}	3.89 ± 0.03^{c}	3.81 ± 0.03^{b}	3.70 ± 0.01^{c}
	Light treated	3.71 ± 0.06^{ab}	3.76 ± 0.01^{ab}	3.72 ± 0.07^{ab}	3.74 ± 0.01^{c}
	Curcumin treated	3.67 ± 0.05^{ab}	3.77 ± 0.00^{b}	3.70 ± 0.04^{ab}	3.63 ± 0.01^{b}
	Photodynamic treated	3.64 ± 0.05^{a}	3.72 ± 0.01^{a}	3.63 ± 0.08^{a}	3.46 ± 0.01^{a}
TA (%)	Untreated	0.54 ± 0.02^{a}	0.59 ± 0.02^{ab}	0.65 ± 0.07^{a}	0.79 ± 0.00^{b}
	Light treated	0.64 ± 0.04^{b}	0.58 ± 0.00^{a}	0.72 ± 0.08^{a}	0.62 ± 0.01^{a}
	Curcumin treated	0.68 ± 0.06^{b}	0.62 ± 0.01^{bc}	0.75 ± 0.03^{a}	0.76 ± 0.00^{b}
	Photodynamic treated	0.60 ± 0.01^{ab}	0.61 ± 0.00^{c}	0.74 ± 0.05^{a}	0.84 ± 0.01^{c}
TSS (%)	Untreated	7.33 ± 0.55^{a}	7.37 ± 0.06^{a}	7.53 ± 0.06^{a}	7.53 ± 0.06^{c}
	Light treated	8.07 ± 0.35^{a}	7.67 ± 0.25^{ab}	7.23 ± 0.40^{a}	6.87 ± 0.06^{b}
	Curcumin treated	8.00 ± 0.56^{a}	8.60 ± 0.10^{c}	6.87 ± 0.67^{a}	6.23 ± 0.06^{a}
	Photodynamic treated	8.10 ± 0.26^{a}	7.77 ± 0.12^{b}	7.63 ± 0.38^{a}	6.80 ± 0.00^{b}

Note: Data are mean ± standard deviation (n = 10, firmness; n = 3, pH, TA, and TSS); for each parameter, data with different letters in the same column are significantly ($p < 0.05$) different.
Abbreviation: nd, not determined.

TABLE 3 Effect of curcumin-mediated photodynamic treatment on firmness, pH, titratable acidity (TA), and total soluble solids (TSS) in "Cabrillo" strawberries during 16-day of storage at 4°C.

		Storage time (day)					
	Treatment	1	4	7	10	13	16
Firmness (N)	Untreated	4.59 ± 1.55^{a}	4.35 ± 1.24^{a}	3.94 ± 1.60^{a}	3.89 ± 0.95^{b}	4.02 ± 1.49^{a}	4.40 ± 1.87^{a}
	Light treated	3.76 ± 2.06^{a}	4.21 ± 1.30^{a}	4.33 ± 1.51^{a}	3.51 ± 0.73^{ab}	3.73 ± 1.22^{a}	4.52 ± 1.65^{a}
	Curcumin treated	4.02 ± 1.69^{a}	3.54 ± 1.31^{a}	3.82 ± 1.50^{a}	3.91 ± 0.62^{b}	4.11 ± 1.30^{a}	4.19 ± 1.11^{a}
	Photodynamic treated	3.94 ± 1.03^{a}	4.23 ± 0.99^{a}	4.77 ± 1.59^{a}	3.14 ± 0.91^{a}	4.20 ± 1.16^{a}	4.34 ± 1.05^{a}
pH	Untreated	3.57 ± 0.03^{a}	3.57 ± 0.06^{a}	3.64 ± 0.03^{b}	3.63 ± 0.01^{a}	3.70 ± 0.12^{a}	3.63 ± 0.09^{a}
	Light treated	3.53 ± 0.04^{a}	3.57 ± 0.09^{a}	3.55 ± 0.05^{a}	3.62 ± 0.03^{a}	3.64 ± 0.04^{a}	3.61 ± 0.05^{a}
	Curcumin treated	3.61 ± 0.07^{a}	3.62 ± 0.10^{a}	3.56 ± 0.03^{ab}	3.61 ± 0.07^{a}	3.59 ± 0.05^{a}	3.63 ± 0.06^{a}
	Photodynamic treated	3.54 ± 0.02^{a}	3.56 ± 0.03^{a}	3.54 ± 0.02^{a}	3.68 ± 0.07^{a}	3.57 ± 0.05^{a}	3.52 ± 0.06^{a}
TA (%)	Untreated	0.83 ± 0.03^{a}	0.79 ± 0.02^{a}	0.80 ± 0.05^{a}	0.74 ± 0.01^{ab}	0.71 ± 0.07^{a}	0.73 ± 0.07^{a}
	Light treated	0.82 ± 0.04^{a}	0.80 ± 0.06^{a}	0.80 ± 0.05^{a}	0.78 ± 0.05^{b}	0.74 ± 0.07^{a}	0.72 ± 0.05^{a}
	Curcumin treated	0.77 ± 0.05^{a}	0.77 ± 0.05^{a}	0.76 ± 0.03^{a}	0.76 ± 0.03^{b}	0.79 ± 0.04^{a}	0.70 ± 0.06^{a}
	Photodynamic treated	0.77 ± 0.05^{a}	0.83 ± 0.03^{a}	0.81 ± 0.03^{a}	0.68 ± 0.01^{a}	0.77 ± 0.03^{a}	0.77 ± 0.03^{a}
TSS (%)	Untreated	6.47 ± 0.61^{ab}	6.17 ± 0.12^{a}	7.00 ± 0.44^{b}	6.13 ± 0.06^{a}	6.33 ± 0.49^{a}	5.87 ± 0.12^{a}
	Light treated	6.20 ± 0.20^{a}	6.37 ± 0.40^{a}	6.07 ± 0.38^{a}	6.50 ± 0.44^{a}	5.93 ± 0.21^{a}	5.73 ± 0.21^{a}
	Curcumin treated	6.90 ± 0.17^{ab}	6.73 ± 0.21^{a}	6.13 ± 0.23^{a}	6.23 ± 0.45^{a}	5.90 ± 0.26^{a}	5.37 ± 0.55^{a}
	Photodynamic treated	7.17 ± 0.12^{b}	6.93 ± 0.40^{a}	6.10 ± 0.00^{a}	6.47 ± 0.40^{a}	6.17 ± 0.15^{a}	5.63 ± 0.40^{a}

Note: Data are mean ± standard deviation (n = 10, firmness; n = 3, pH, TA, and TSS); for each parameter, data with different letters in the same column are significantly ($p < 0.05$) different.

could also be related to the increased microbial growth during storage, which can adversely affect the integrity of fruit surface and thus induce a higher moisture loss leading to a higher weight loss. This is in accordance with the obtained microbial results (Figure 2). Moreover, photodynamic treatment may have the potential to induce tissue damage, which may result in increased metabolic activity and subsequently increased weight loss. However, a few studies have indicated that effective antimicrobial photodynamic treatment does not necessarily lead to plant phototoxicity or tissue damage (Chai et al., 2021; Hamminger et al., 2022). However, this needs to be further studied as various factors such as type and concentration of photosensitizer, light intensity, and dose can influence the tissue damage. Similar patterns of increased weight loss were observed in fresh strawberries subjected to other preservation techniques, such as limonene nano-coating (Dhital et al., 2018) and pulsed light (Duarte-Molina et al., 2016). The former may cause alterations in the surface properties of strawberries and result in an increase in surface permeability to water vapor, thereby leading to greater moisture loss from the fruit. However, the latter treatment may stimulate metabolic activity through oxidative damage, causing cellular damage to the outer layers of fruit tissues and disrupting their barrier function, and therefore allowing for greater water loss through respiration.

3.6 | Color properties

Color is a critical quality factor influencing the perception of freshness in fruits, including strawberries. The effect of curcumin-mediated photodynamic treatment on the color properties of fresh "Red Rhapsody" and "Cabrillo" strawberries during storage was evaluated, and results are present in Tables S1 and S2, respectively. Generally, fruit color is described by parameters like L^* (lightness), hue, and chroma (color intensity). The results showed that the different treatments did not alter the color properties of strawberries either after treatment or during storage (Tables S1 and S2). For "Red Rhapsody," the values of L^*, hue, and chroma at day 1 were around 35.66–36.17, 19.02–19.33, and 21.21–21.94, respectively. In the case of "Cabrillo," these values were 34.92–35.70, 27.51–28.78, and 36.51–37.84, respectively. Furthermore, there was no significant difference in the chromaticity b^* value (yellowness value) between the untreated and curcumin-/photodynamic-treated samples (Tables S1 and S2), which indicates that the concentration and amount of curcumin applied did not have any significant dyeing effect on the fruits. These findings demonstrate that curcumin-mediated photodynamic treatment left the color properties of strawberries unaltered post-treatment. However, changes were observed during storage, with "Red Rhapsody" strawberries displaying their lowest L^* and peak chroma values on day 10 (Table S1), and "Cabrillo" strawberries exhibiting these shifts on days 13 and 16 (Table S2). Collectively, the results firmly established that the impact of photodynamic treatment on strawberry color properties remained absent, both after treatment and during storage. This aligns with other research suggesting that preservation methods, such as gamma irradiation (Shankar et al., 2021) or exposure to methyl jasmonate and ethanol volatiles (Ayala-Zavala et al., 2004), also did not significantly influence strawberry color.

3.7 | Total soluble solids, pH, and titratable acidity

The values for TSS, pH, and TA were evaluated for both "Red Rhapsody" and "Cabrillo" strawberries (Tables 2 and 3). Photodynamic-treated "Red Rhapsody" strawberries exhibited a significantly higher TSS on day 5 compared to untreated fruits (7.77% vs. 7.37%), which was conversely lower on day 15 (Table 2). In the case of "Cabrillo" strawberries, treatment differences were non-significant, except on day 7, where photodynamic-treated fruits displayed a significantly lower TSS (6.10%; Table 3). It is worth noting that TSS in strawberries can be influenced by metabolic reactions, degree of maturity (Mitcham, 2007; Treviño-Garza et al., 2015), which can potentially lead to an increase in sugars and soluble solids. However, the utilization of reducing sugars in fruit respiration (Almenar et al., 2009) can result in decreased TSS content. The literature presents a divergence of findings, with some studies reporting increases (Peretto et al., 2014; Treviño-Garza et al., 2015) and others reporting decreases (Cao et al., 2010; Jiang et al., 2020) in TSS of strawberries during storage.

Additionally, a decreasing trend was observed in TA of strawberries over the storage period (Tables 2 and 3). For photodynamic treated "Red Rhapsody" strawberries, their acidity was significantly higher than that of untreated fruits during storage, except for day 10 (Table 2). This is in accordance with the reduction in TA values observed in strawberries treated with blue light during a 12-day storage at 5°C, where treated fruits showed higher TA values than untreated ones (Xu et al., 2014). In contrast, TA of "Cabrillo" strawberries was shown to be unaffected by treatment during storage (Table 3). Factors such as fruit respiration and microbial growth can contribute to decreased TA by utilizing organic acids as carbon sources (Echeverria & Valich, 1989; Hernández-Muñoz et al., 2008).

4 | CONCLUSION

This study provides significant insights into the potential of curcumin-mediated photodynamic treatment for reducing decay in strawberries. The decontamination efficacy was found to be influenced by curcumin concentration, with a 20% reduction in decay incidence for photodynamic-treated strawberries using 32.5 μmol L^{-1} curcumin. While the microbial count showed that photodynamic treatment was not able to control the microbial growth during storage. Furthermore, the color and firmness of strawberries remained unaltered by the treatment. While results show a clear trend of reduced decay and quality deterioration in photodynamic-treated strawberries, further research is needed to identify key processing variables for consistent and effective microbial reduction. This includes optimizing conditions such as photosensitizer concentration, light exposure, and surface drying. It is also essential to explore the impact of the treatment on sensory, nutritional, and phytochemical attributes during storage. The observed reduction in decay without compromising fruit quality not only can help reduce waste and save costs for retailers and suppliers but also aligns with consumer preferences for sustainable and chemical-free products. Although the initial investment in specialized equipment for photodynamic treatment may be significant, the long-term benefits of reduced spoilage and extended shelf life can outweigh these costs. Overall, photodynamic treatment shows promise as an environmentally friendly decontamination technique, potentially applicable to other fresh produce varieties.

AUTHOR CONTRIBUTIONS

Maral Seididamyeh: Conceptualization; methodology; investigation; writing—original draft; formal analysis. **Michael E. Netzel**: Writing—review and editing; supervision. **Ram Mereddy**: Supervision; writing—review and editing. **Yasmina Sultanbawa**: Writing—review and editing; supervision; funding acquisition; resources.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of Interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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