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Research Article

Synergistic Utilization of ε-Polylysine and p-Coumaric Acid as Natural Preservatives for Enhancing the Shelf Life of Fresh-Cut Green Bell Peppers

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The utilization of natural preservatives presents a promising avenue for mitigating the spoilage of fresh-cut fruits and vegetables induced by microorganisms, enzymatic browning, and water loss. We have developed an innovative method for preserving fresh-cut green peppers using the combined effects of ε-polylysine (ε-PL) and p-Coumaric acid (p-CA). Through concentration screening experiments, we determined that the optimal concentrations of ε-PL and p-CA were 25 mg/L and 10 mg/L, respectively (ε-p-CA). Treatment with ε-p-CA significantly improved the quality of fresh-cut green peppers. It effectively reduced hardness and weight loss, preserving the texture and appearance of the peppers. Furthermore, ε-p-CA treatment delayed the increase in respiratory rate, electrolyte leakage, and ethylene production, thereby maintaining the structural integrity. Meanwhile, ε-p-CA treatment effectively inhibited the malondialdehyde (MDA) content increase and maintained DPPH radical scavenging activity. The microbial analysis demonstrated the ε-p-CA-treated peppers also showed lower total bacterial, mold, and yeast counts, which prolonged the freshness of fresh-cut peppers. In addition, ε-p-CA treatment improved the retention of phenolics and vitamin C without significantly affecting the color and soluble sugar content of green peppers. Overall, the ε-p-CA treatment showed promise as a natural preservative for extending the shelf life of fresh-cut green peppers.

1. Introduction

With the rapid pace and increasing diversity of society, there is a rising demand for precut fruits and vegetables, which are gaining popularity due to their convenience and nutritional benefits [1]. Nevertheless, the fragile cellular structure of freshly cut fruits and vegetables, microbial proliferation, enzymatic browning, and moisture loss render them more susceptible to putrefaction and deterioration, thereby curtailing their shelf life. This has engendered substantial agricultural wastage and economic losses [2]. Henceforth, the development of efficacious and secure preservation techniques for freshly cut agricultural products has emerged as a pivotal quandary within the realm of the food industry [3]. Although conventional methods for preserving fruits and vegetables involve the use of chemical preservatives like hydrogen sulfide and sodium benzoate, their effectiveness is limited due to concerns related to food safety, environmental impact, and preservation efficacy [4]. In recent years, the pursuit of developing novel methods for preserving freshly cut fruits and vegetables has emerged as the foremost endeavor of researchers in the relevant scientific community. Meng et al. employed pressurized argon gas treatment on freshly cut cucumbers to prolong their shelf life [5]. Similarly, Elias et al. investigated the application of electron beam irradiation as a preservation technique for fresh raspberries, demonstrating its effectiveness in maintaining quality and extending storage life [6]. However, the implementation of these physical preservation techniques often involves substantial expenses and presents hurdles in terms of promotion and widespread adoption [7].

In recent times, there has been a growing focus on approaches that amalgamate natural preservatives with other preservation methodologies. FM Pintos et al. effectively employed riboflavin to prolong the shelf life of fresh-cut green

peppers under specific conditions of 94% relative humidity and a temperature of 4°C [8]. Ali et al. successfully utilized L-cysteine to retard the enzymatic browning and decay of lychee fruits under controlled conditions of 90 ± 5% relative humidity and a temperature of 5 ± 1°C [9]. Concurrently, we have observed the potential of ε-PL and p-CA as natural compounds with antibacterial and antioxidative properties. ε-PL, a poly-L-lysine polymer, exhibits a broad-spectrum antibacterial activity against bacteria, yeast, and fungi and has received approvals from regulatory agencies such as the FDA and EFSA as a recognized safe and edible natural preservative [10]. Lan et al. demonstrated the remarkable ability of ε-PL to effectively impede the disruption and impairment of cellular membranes caused by *Shewanella putrefaciens*, indicating its potent membrane-stabilizing properties [11]. p-CA, a natural phenolic compound found in plants, has a variety of biological activities such as antioxidant, antibacterial, anticancer, and anti-inflammatory [12, 13]. Ismail et al. demonstrated the robust efficacy of the p-CA in effectively scavenging free radicals, making it a valuable tool for mitigating or inhibiting lipid oxidation in food matrices and preventing the formation of detrimental oxidation byproducts [14]. Despite ε-PL being acknowledged as a natural antimicrobial agent and p-CA possessing potent antioxidant characteristics, there is a scarcity of literature addressing the synergistic utilization of these two components for the preservation of fresh-cut fruits and vegetables.

In the present investigation, fresh-cut bell peppers were subjected to a treatment involving the combined application of ε-PL and p-CA. It is widely recognized that the storage limit for freshly cut green peppers is 7 days at 7°C [15]. Meanwhile, storing fresh-cut bell peppers at temperatures below 7°C can induce physiological and metabolic perturbations, compromising membrane integrity and impairing disease resistance capabilities [16]. In order to counteract the adverse effects of low-temperature-induced cold injury and excessive moisture loss on the quality of fresh-cut bell peppers, we implemented storing them under controlled conditions of 8 ± 1°C temperature and 92 ± 2% relative humidity. The preservation efficacy of bell peppers was investigated with regard to their physicochemical attributes, nutrient profile, and microbial population, aiming to offer a practical guideline for preserving the freshness of fresh-cut bell peppers.

2. Materials and Methods

2.1. Materials. Green bell peppers (He Jiao 13) were procured from Jinzhong Huilong Farmers' Market, while polylysine (MV2000–5000), phenol, and trichloroacetic acid were obtained from Shanghai Aladdin Biochemical Technology Co. P-Coumaric acid (purity ≥ 98%), 2-thiobarbituric acid, 2,6-dichloroindophenol, and 1,1-diphenyl-2-bitter hydrazine (DPPH) were sourced from Shanghai Yuanye Biotechnology Co. All other chemical reagents employed were of analytical grade.

2.2. Concentration Selection

2.2.1. Concentration Optimization of ε-PL. To explore the impact of varying concentrations of ε-PL on the freshness of fresh-cut green bell peppers, the peppers were subjected to sequential processes of deionized water washing, gentle drying, and immersion in a sodium hypochlorite solution of 100 mg/L for a duration of 1 min. Subsequently, the embryos and seeds of the peppers were removed, and the remaining flesh was sliced longitudinally with a sharp knife into strips measuring 2.5 × 1.5 cm. From each experimental group, 30 slices of green bell pepper (about 5–7 grams per slice) were chosen and immersed in ε-PL solutions (25°C) with concentrations of 0, 5, 10, 15, 20, and 25 mg/L for 5 min. Following that, the samples were gently air-blown for drying and then arranged in white polypropylene trays ($L \times W \times H = 335 \times 255 \times 4$ mm). To mitigate excessive carbon dioxide buildup, a total of 20 evenly spaced 2 mm diameter air permeation holes were punctured above the cling film-covered trays. Finally, the trays were placed in a refrigerated cabinet maintained at a controlled temperature of 12 ± 1°C and relative humidity of 92 ± 2% for a duration of 10 days (Figure 1(a)), during which the incidence of decay was meticulously documented. The incidence of decay was evaluated using a hedonic four-level (0–3) intensity scale (0 = healthy individuals; 1 = the presence of brown spots less than or equal to 2; 2 = the number of brown spots greater than 2; 3 = the presence of obvious mold spots with visible mycelial growth). The incidence of decay was calculated by the formula $\sum$ = (2, 3 number)/total number, and the experiment was repeated three times.

2.2.2. Concentration Optimization of ε-p-CA. To further examine the influence of varying concentrations of p-CA on the freshness of fresh-cut bell peppers, the optimal ε-PL concentration, as determined in Section 2.2, was employed. Fresh-cut peppers were immersed in a composite solution containing p-CA and ε-PL at concentrations of 0, 5, 10, 15, 20, and 25 mg/L, respectively, for a duration of 5 min. Subsequently, the samples were subjected to gentle air blowing for drying and stored in a freezer maintained at a temperature of 12 ± 1°C and a relative humidity of 92 ± 2% for a duration of 10 days (Figure 1(a)). Throughout this storage period, the incidence of decay was recorded.

2.2.3. Determination. Based on the results of the preliminary screening, the formulation consisting of an ε-PL concentration of 25 mg/L and a p-CA concentration of 10 mg/L (pH = 6.2) was selected as the optimal combination. The samples were placed in polypropylene trays and covered with perforated cling film, ensuring proper ventilation. Subsequently, they were stored under controlled conditions of 8 ± 1°C and 92 ± 2% relative humidity (Figure 1(b)). Sampling was conducted on days 0, 3, 6, 9, and 12 to evaluate various physical and chemical properties including weight loss, hardness, color variation, electrolyte leakage, malondialdehyde content, respiration rate,

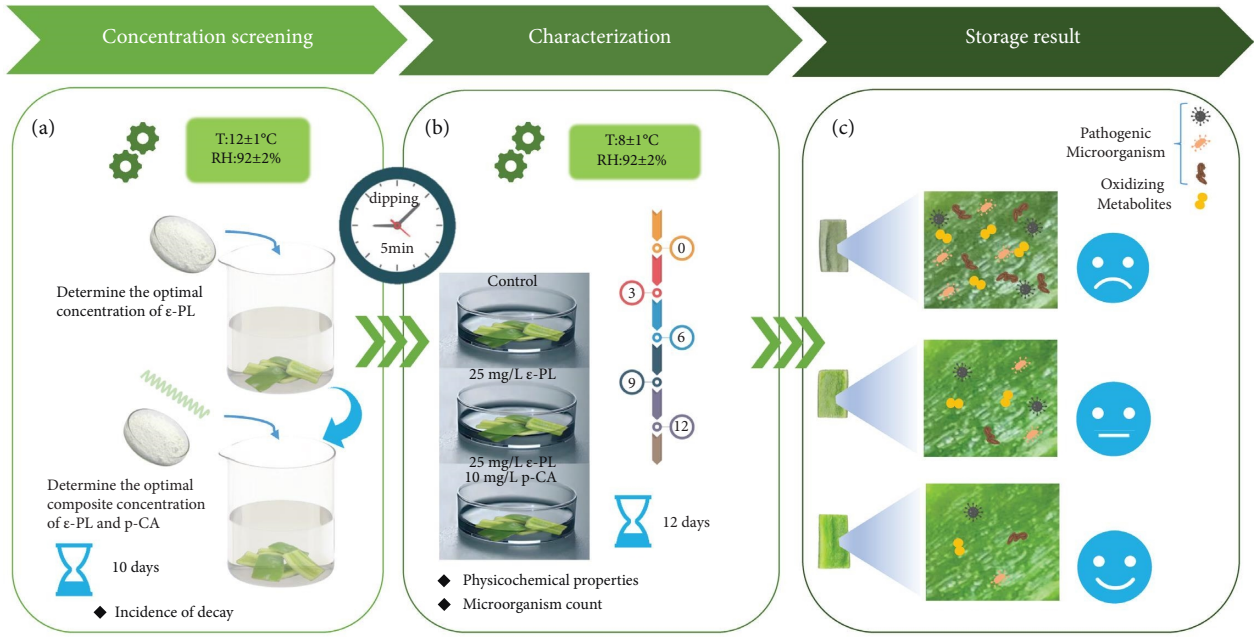

Figure 1: Experimental design and quality change diagram.

ethylene content, and antioxidant capacity. In addition, the nutrient composition including soluble sugars and Vc was analyzed. Finally, microbial enumeration was performed to evaluate the presence of bacteria, mold, and yeast.

2.3. Physical and Chemical Properties

2.3.1. Weight Loss. To explore the impact of ε-PL and p-CA on the water loss of fresh-cut green bell peppers, weight loss experiments were performed. The trays containing the fresh-cut green bell peppers were weighed at specific time points, including days 0, 3, 6, 9, and 12. The rate of weight loss was then calculated using the following equation:

$$\text{Weight loss}\,(\%) = \frac{(m_1 - m_t)}{(m_1 - m_0)} \times 100\%, \tag{1}$$

where m_1 denotes the initial weight of the sample, m_t denotes the weight of the sample on days 0, 3, 6, 9, and 12, and m_0 denotes the weight of the tray. Three replicate measurements were performed for each group of samples.

2.3.2. Hardness. To examine the effect of ε-PL and p-CA on the tissue properties of fresh-cut green bell peppers, the hardness was measured using a texture analyzer (TA.XT.plus SMS UK). Puncture testing was carried out on the pepper's peel using a P2 probe at a controlled speed of 1 mm/s and a strain setting of 80%. A total of 30 measurements per sample group were taken, with five random measurements per pepper.

2.3.3. Color. To study the influence of ε-PL and p-CA on the hue of freshly sliced green bell peppers, a random evaluation of the color of the pepper samples was conducted employing the colorimeter (NH310, ThreeNH Technology, Shenzhen, China) according to the Yildiz et al. method. A total of 30 measurements were carried out for each group. L^* is defined as luminosity, a^* (±red-green) signifies the redness, and b^* (±yellow-blue) conveys the yellowness [17]. The overall color variation (ΔE) is computed using the following equation:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \tag{2}$$

where ΔL, Δa, and Δb are the color parameter differences between samples and standard samples in each group.

2.3.4. Electrolyte Leakage (EL). To explore the impacts of ε-PL and p-CA on the permeability of cell membranes in fresh-cut green bell pepper, the measurement of electrolyte leakage was carried out using a conductivity meter (DDS-307, Yidian Science, Shanghai, China). With slight modifications based on the approach by Ali et al., a beaker was filled with 50 mL of distilled water, followed by the addition of 25 g of green pepper slices [18]. The mixture was then incubated at 25°C for 20 min. After incubation, the initial solution conductivity E_0 was measured. Subsequently, the beaker containing the sample was boiled for 15 min, allowed to cool down to 25°C, and the final solution conductivity E_1 was measured. Each experimental group consisted of three replicates. The electrolyte leakage was determined using the subsequent equation:

$$\text{EL}\,(\%) = \frac{E_0}{E_1} \times 100\%. \tag{3}$$

2.3.5. Malondialdehyde (MDA) Content. Malondialdehyde (MDA) is a commonly used biomarker for lipid peroxidation, providing a means to assess the extent of oxidative damage to cell membranes in various biological systems [19]. Following the methodology described by Ali et al.[18],

Initially, 10 g of green bell pepper samples were obtained and homogenized using a tissue mashing homogenizer (JJ-2, Guohua Electric, Changzhou, China) after the addition of 50 mL of trichloroacetic acid solution with a concentration of 0.1 g/mL. The resultant mixture was then centrifugation at $10,000 \times g$ for a duration of 20 min at a temperature of 4°C. Subsequently, 4 mL of the supernatant was combined with an equal volume of thiobarbituric acid solution at a concentration of 6.7 g/L. The mixture was incubated in a boiling water bath for 20 min, followed by cooling and another round of centrifugation for 10 minutes. The absorbance of the supernatant was measured at 450 nm, 532 nm, and 600 nm using a double-beam UV-visible spectrophotometer (TU-1901, Beijing Puxi General Instrument Co., China), and the measured absorbance values were recorded. The MDA content was calculated using the following formula:

$$\mathrm{MDA}\left(\frac{\mu\mathrm{mol}}{\mathrm{g}}\right) = \left[6.45 \times \left(\mathrm{OD}_{532} - \mathrm{OD}_{600}\right) - 0.56 \times \mathrm{OD}_{450}\right] \times \frac{V_t}{\left(V_s \times m\right)}, \tag{4}$$

where V_t represents the total volume of the extract, V_s denotes the volume of the extract utilized for the reaction, and m signifies the mass of the sample. Each sample group underwent three replicates.

2.3.6. Respiration Rate and Ethylene Content. The effects of ε-PL and p-CA on the freshness of fresh-cut bell peppers were evaluated by measuring the respiratory rate and ethylene production. Following the methodology described by Prasad et al. [20], approximately 80 g of pepper samples were placed into a 500 mL beaker, and sealed with cling film. The beaker was then incubated at 25°C for 20 min. Subsequently, 30 mL of gas was accurately extracted from the beaker using a $C_2H_4/O_2/CO_2$ analyzer (F-940, Yangguangyishida, Beijing, China) to determine the CO_2 content. The obtained results were expressed as the mass of CO_2 generated per kilogram of fresh weight within a 1 h timeframe (mg).

Afterward, the $C_2H_4/O_2/CO_2$ analyzer was calibrated using an ethylene tube, and the same procedure was repeated to determine the amount of ethylene in the beaker. The ethylene content was expressed as the volume fraction (μL) of ethylene produced per kg of fresh weight in 1 h. Three replicate measurements were performed for each group of samples.

2.3.7. DPPH (2,2-Diphenyl-1-Picrylhydrazyl) Free Radical Scavenging Activity. The effects of ε-PL and p-CA on the antioxidant activity of fresh-cut bell peppers were evaluated using the DPPH assay [1]. 10 g of samples were acquired and ground. The resulting homogenate was then centrifugation at $16000 \times g$ for 30 min at 4°C. Subsequently, 0.02 mL of the supernatant was combined with 7.8 mL of a methanol solution containing DPPH at a concentration of 25 mg/L. The mixture was thoroughly shaken and allowed to incubate for 30 min. The absorbance of the reaction solution was measured at 517 nm. The DPPH radical scavenging rate was determined using the subsequent equation:

$$R_{\mathrm{DPPH}}(\%) = \left(1 - \frac{A_s}{A_{\mathrm{DPPH}}}\right) \times 100\%, \tag{5}$$

where A_{DPPH} represents the absorbance of the DPPH-methanol solution, while A_s denotes the absorbance of the DPPH-methanol solution when mixed with the green pepper solution.

2.3.8. Total Phenolic Content (TPC). To examine the effect of ε-PL and p-CA on the antinutritional and antioxidant properties of fresh-cut bell peppers, the total phenolic content was assessed utilizing the Folin–Ciocalteu reagent method [21]. A 5 g sample of green peppers frozen in liquid nitrogen was taken and ground. Incorporate this fine powder into a solution consisting of 30 mL of 95% ethanol, extract it for a duration of 5 min, and then adjust the volume to 50 mL. Subsequently, the obtained extract was centrifugation at $15000 \times g$ for 10 min. A volume of 0.6 mL of the resulting supernatant was combined with 4.5 mL of Folin–Ciocalteu solution with a concentration of 1 mol/L and incubated for 5 min. Following this, 0.6 mL of Na_2CO_3 solution with a concentration of 10% was added and allowed to react for 60 min under light-protected conditions. The absorbance at a wavelength of 765 nm was measured, and the total phenolic content was calculated using the gallic acid standard curve:

$$\mathrm{TPC}\left(\frac{\mathrm{mg}}{100\mathrm{g}}\right) = \frac{\left(C_1 \times V_T\right)}{\left(V_s \times F_w\right)}, \tag{6}$$

where V_T is the total volume of the extract, C_1 is the total phenol content of the standard curve check, V_s is the volume of the supernatant taken, and F_w is the sample mass. Each group of samples was repeated three times.

2.4. Nutrient Composition Determination

2.4.1. Soluble Sugar Content (SSC). To assess the impact of ε-PL and p-CA on the soluble sugar content in fresh-cut bell peppers, the phenol-sulfuric acid method was employed for its determination [22]. Approximately 10 g of green pepper samples were frozen in liquid nitrogen and subsequently ground into a fine powder. Precisely 1 g of the green pepper powder was weighed and combined with 10 mL of water, followed by extraction in boiling water for a duration of 30 min. Extract 0.5 mL of the sample solution and mix it with 1 mL of phenol solution with a concentration of 0.9 g/L and 5 mL of concentrated sulfuric acid. Allow the mixture to stand at room temperature for a duration of 30 min, following which the absorbance of the resulting solution is measured at a wavelength of 485 nm. Calculation of soluble sugar content using the sucrose standard curve:

$$\mathrm{SSC}\left(\frac{\mathrm{g}}{100\,\mathrm{g}}\right) = \frac{(m' \times V \times N)}{\left(V_s \times m \times 1\,0^6\right)} \times 100\%, \quad (7)$$

where m' is the mass of sucrose (μg) from the standard curve, V is the total volume of sample extract (mL), N is the dilution multiple, V_s is the volume of extract (mL) taken for the determination, and m is the mass of sample (g)

2.4.2. Vitamin C Content (Vc). To study the impact of ε-PL and p-CA on the vitamin C (Vc) content in fresh-cut bell peppers, the 2,6-dichlorophenol indophenol method was employed for its quantification [23]. A quantity of 10 g of green pepper was taken and combined with 10 mL of a 2% oxalic acid homogenate, which was then diluted to a final volume of 50 mL. Subsequently, 5 mL of the resulting extract was transferred into a conical flask, and the 2,6-dichlorophenol indophenol extract was added dropwise from a microburette until a persistent red color emerged without any further color change within a duration of 15 seconds. The volume of the extract required for the titration was recorded. The Vc content was calculated using the subsequent equation:

$$\mathrm{Vc}\left(\frac{\mathrm{mg}}{100\,\mathrm{g}}\right) = K \times \frac{(V_1 - V_0)}{m} \times V_s, \quad (8)$$

where K represents the titration factor, V_1 denotes the volume of 2,6-dichlorophenol indophenol solution consumed during the titration of the sample (mL), V_0 signifies the volume of 2,6-dichlorophenol indophenol solution consumed during the blank titration (mL), V_s represents the volume of the sample liquid used in the titration (mL), and m signifies the mass of the sample (g). Each sample group underwent three replicate measurements.

2.5. Microbiological Analysis. Microbial analysis serves as a crucial indicator in assessing the quality of freshly sliced green bell peppers. To assess the impact of ε-PL and p-CA treatment on the microbial quality of fresh-cut green bell peppers, a quantitative analysis of bacterial, mold, and yeast populations was conducted using the plate count method, following the National Standard of the People's Republic of China [24]. 25 g of the sample within aseptic pouches, infusing them with 225 mL of sterile physiological saline solution, boasting a concentration of 0.85 g/100 mL, and agitate the mixture for a duration of 3 min. Subsequently, enact a tenfold serial dilution of the solution, aspirating 0.1 mL of the diluted solution and introducing it into beef extract peptone agar medium (for aerobic bacteria) and chloramphenicol yeast glucose agar medium (for molds and yeast). These cultures shall then be incubated at 37°C for 3 days and 25°C for 5 days, respectively. Repeat three times for each set of samples.

2.6. Statistical Analysis. Data analysis was conducted using SPSS Statistics 25 software, and the results were presented as the mean ± standard deviation. Subsequently, the data were subjected to a one-way analysis of variance (ANOVA), followed by post hoc analysis using Duncan's multiple range test. Statistical significance was considered at a threshold of $P < 0.05$.

3. Results and Discussion

3.1. Impact of ε-PL and p-CA Concentrations on the Quality of Green Bell Pepper. To explore the influence of different concentrations of ε-PL on the preservation efficacy of fresh-cut green bell peppers, screening experiments were carried out (Figure 2(a)). Treatment groups with ε-PL concentrations of 0, 5, 10, 15, 20, and 25 mg/L were used to observe statistics on the incidence of decay in fresh-cut bell peppers. Over the course of day 10, the decay rate of green bell pepper slices exhibited a progressive decline in tandem with the elevation of ε-PL concentration. In the control group, the incidence of decay reached a staggering 43%. On the cross-sections of freshly sliced green bell peppers, a profuse leakage of nutrients occurred, thereby providing the essential sustenance for microbial proliferation and consequently hastening the deterioration of the pepper's quality. Simultaneously, we also observed that even when the concentration of ε-PL was between 5 mg/L and 10 mg/L, a notably high decay rate persisted, with no discernible differences compared to the control group. As the concentration of ε-PL is further augmented, the incidence of decay undergoes a pronounced reduction. The preservation outcome was found to be the most favorable at a concentration of 25 mg/L, leading to a remarkable decay rate of only 20%. Owing to its expansive spectrum of bacteriostatic properties, ε-PL proficiently suppresses enzyme activities associated with both bacterial respiratory and cellular metabolism. This dual inhibition not only curtails bacterial cellular growth but also heightens cellular membrane permeability, ultimately culminating in cellular demise [11]. The findings indicated that the ε-PL concentration of 25 mg/L exerted a notable effect in mitigating the decay of fresh-cut green bell pepper, thus enhancing its preservation of freshness.

The influence of p-CA concentration on fresh-cut green bell peppers was studied while maintaining a constant ε-PL concentration of 25 mg/L (Figure 2(b)). The incidence of decay within each treatment group was 20%, 16.7%, 11%, 12%, 15.7%, and 22% with the addition of p-CA at 0, 5, 10, 15, 20, and 25 mg/L. The results suggested that as the p-CA concentration increased, the incidence of decay in fresh-cut green bell pepper initially exhibited a decline and subsequently displayed an upward trend. Upon reaching a concentration of 10 mg/L, p-CA demonstrated the lowest incidence of decay. This phenomenon can be attributed to the capacity of an optimal p-CA concentration to effectively counteract the generation of free radicals during metabolic processes and delay the formation of harmful oxidation products [13]. Concurrently, the presence of appropriate ε-PL inhibited the growth and proliferation of microorganisms, contributing to the preservation of freshness [25]. Nevertheless, an elevation in p-CA concentration beyond the optimal level triggered an interaction between polyphenol oxidase (PPO) present on the surface of the peppers and p-CA, leading to the generation of black pigments in the

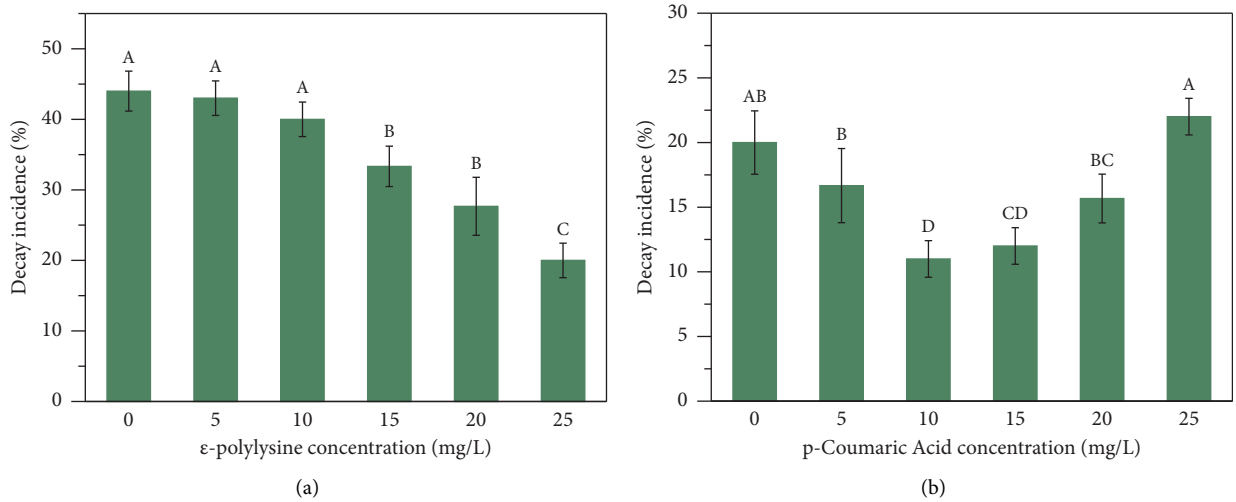

Figure 2: Effect of ε-polylysine and p-Coumaric acid concentrations on the quality of bell pepper. Effect of ε-polylysine concentration of 0, 5, 10, 15, 20, and 25 mg/L on fresh-cut green pepper fresh preservation (a); effect of ε-polylysine concentration of 25 mg/L and p-CA concentration of 0, 5, 10, 15, 20, and 25 mg/L on fresh-cut green pepper fresh preservation (b). Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

presence of oxygen. This undesirable consequence intensified the browning process in fresh-cut bell peppers, ultimately compromising their overall freshness [26].

3.2. Freshness Preservation Performance. The quality of fresh-cut green bell peppers depends on their own oxidative respiration, microbial infection, and moisture loss [2]. As depicted in Figure 3, during the entire storage duration, the three groups of samples exhibited no conspicuous disparities in their outward appearance of the preceding day 6, closely correlated with suitable storage temperatures and elevated relative humidity. However, the control group began manifesting evident alterations in appearance on day 9, displaying browning lesions on the cut surfaces and extensive rot and fungal growth on day 12. In the absence of any treatment, the fragile cellular structure of the cross-sections of fresh-cut bell peppers led to the leakage of nutrients. Concurrently, microbial attachment and proliferation further weakened the pepper's innate defenses, resulting in a rapid decline in quality during the later stages of storage. Previous studies have reported a maximum shelf life of day 7 for freshly sliced green bell peppers, consistent with the findings of this study [15]. Notably, the ε-PL group exhibited a certain degree of lesion development on day 12, whereas the ε-p-CA group displayed only minor blemishes. Thus, it is visually apparent that the combined treatment of ε-PL and p-CA significantly mitigates the deterioration of the quality of freshly sliced green bell peppers.

3.3. Physical and Chemical Properties

3.3.1. Weight Loss. Figure 4(a) illustrates the weight loss rate of green bell pepper slices throughout the storage period. On day 3, exhibited no significant disparity among the three groups exhibited no significant disparity among the three groups. As time elapsed, starting from day 6, the weight loss rate in the control group demonstrates a noteworthy disparity when compared to the ε-PL group (2.71%) and the ε-p-CA group (2.56%). This considerable increase in weight loss signifies a rapid deterioration in the quality of green pepper slices. On day 9, the weight loss rate in the control group had reached 6.39%, exceeding the reported acceptable limit of 5% for fresh-cut green pepper consumers [15], while the ε-p-CA group maintained a weight loss rate of 4.32%, well within the acceptable range for consumers. On day 12, the ε-p-CA group displayed the lowest weight loss rate of 7.39%, which was significantly different from the weight loss rates of 9.14% in the ε-PL group and 10.58% in the control group ($P < 0.05$). The findings reveal that all experimental groups exhibited a decline in weight during the storage period, primarily attributed to intrinsic oxidative metabolism and transpiration dehydration processes. However, the ε-p-CA group demonstrated the minimal weight loss, likely attributed to p-CA's role in scavenging reactive oxygen species on the surface of fresh-cut green bell pepper, thereby mitigating metabolic reactions [27]. Concurrently, ε-PL effectively inhibits microbial attachment and growth, thus retarding the consumption of nutrients [25].

3.3.2. Hardness. As depicted in Figure 4(b), throughout the entire storage period, the hardness of the control group gradually diminished, with a more pronounced decline commencing on day 3. In contrast, both the ε-PL and ε-p-CA groups exhibited a slight decrease in hardness during the storage period. On day 6, the hardness of the control group measured (4.55 ± 0.24) N, while the ε-p-CA group recorded (4.84 ± 0.19) N, signifying a significant disparity, akin to the observations made by Ranjeet Singh in his research [23]. The swift decline in hardness within the control group can be attributed, on the one hand, to the substantial consumption of its intrinsic nutrients, leading to the disintegration of its tissue

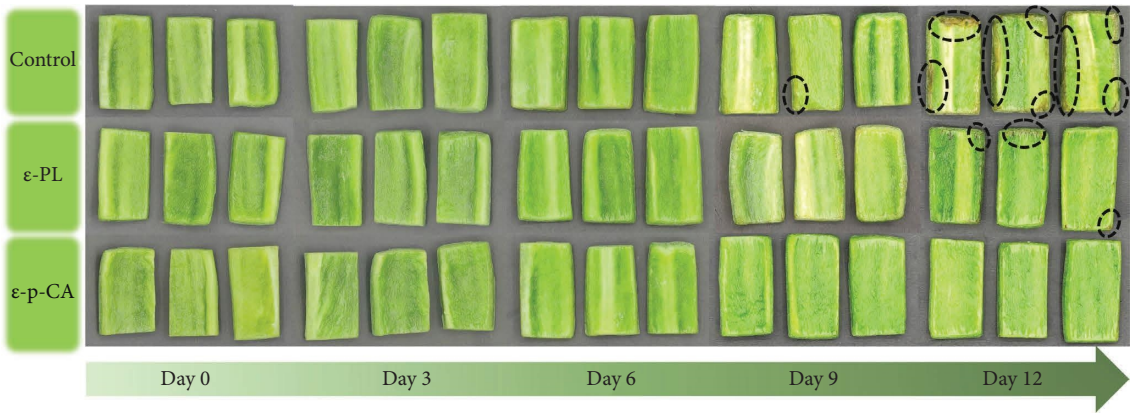

FIGURE 3: Photographs of the untreated green pepper slices and ε-polylysine alone and in combination with p-Coumaric acid treated green bell pepper slices during 12 days storage period at 8°C.

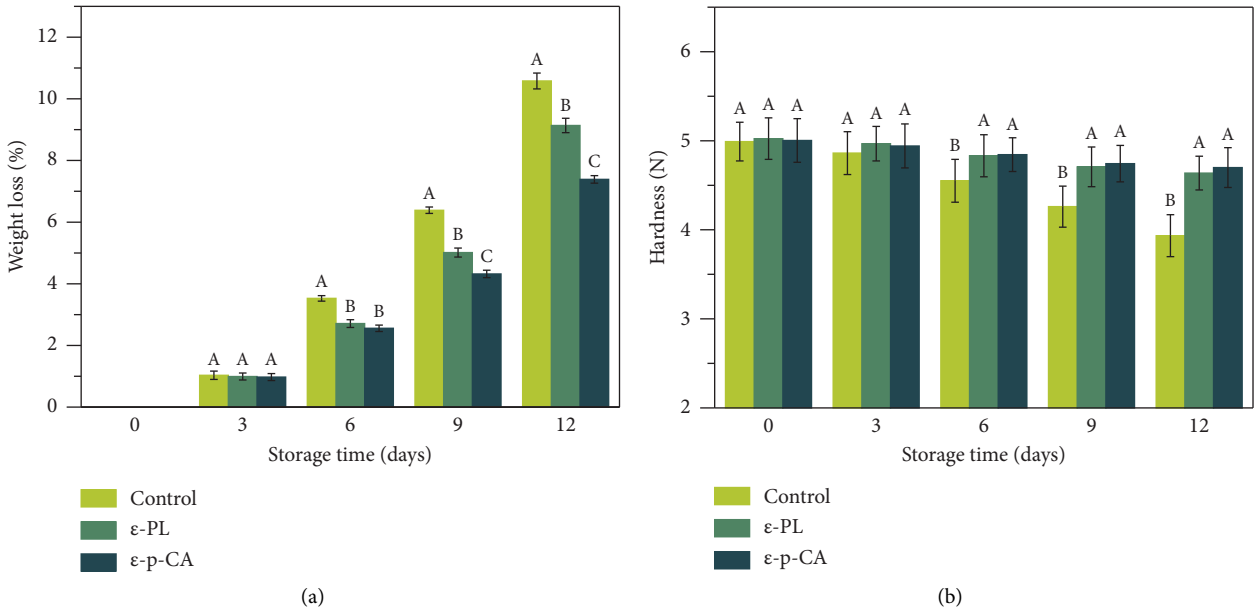

FIGURE 4: During a 12-day storage period at 8°C, weight loss (a) and hardness (b) changes in green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid. Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

structure. On the other hand, the lack of inherent immunity, coupled with microbial intrusion in the pepper slices, further expedited the consumption of nutrients and the evaporation of moisture. On day 12, the control group's hardness had declined by 21.2%, whereas the ε-PL and ε-p-CA groups had decreased by 7.6% and 6.0%, respectively. Chen et al. used chitosan-catechin coating to treat satsuma oranges and also observed a progressive decrease in the hardness of sweet oranges during storage [28]. This is likely due to the attachment of ε-PL and ε-p-CA to the surface of the bell peppers, retarding the oxidative respiration process responsible for the depletion of intrinsic nutrients and aligning with the measured weight loss indicators. The foregoing results underscore the potential of ε-PL and ε-p-CA as preservatives for fresh-cut bell peppers, serving as additives for food preservation.

3.3.3. Color. The color values of green pepper slices throughout the storage period are presented in Table 1. Regarding the brightness (L^*) parameter, no significant disparity was observed between the control group and the treatment groups at the commencement of storage. A slight elevation in brightness was discernible on day 3, followed by consistent maintenance of this level throughout the storage period. The ε-p-CA group showed a slight decrease of 1.25 units on day 6. On day 12, no significant distinction in brightness was observed among the three sample groups ($P > 0.05$). Regarding the red-greenness (a^*) parameter, all three sample groups fluctuated slightly during the storage period, maintaining values within acceptable ranges. Notably, the ε-p-CA group displayed an increase of 0.81 units on day 6, indicating a lesser decline in green color intensity. Similarly, Pintos et al., in their study using riboflavin in the treatment of fresh-cut green peppers, also found that the color difference

Table 1: During a 12-day storage period at 8°C, color (L^*, a^*, b^*, ΔE) changes of green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid.

Color parameters	Samples	Storage time				
		0	3	6	9	12
L^*	Control	37.28 ± 0.60^a	38.27 ± 0.75^a	37.27 ± 0.73^a	37.18 ± 0.86^a	36.77 ± 0.50^a
	ε-PL	37.52 ± 0.78^a	38.09 ± 0.86^a	37.40 ± 0.53^a	37.08 ± 0.88^a	37.37 ± 0.82^a
	ε-p-CA	37.45 ± 0.57^a	38.14 ± 0.70^a	36.59 ± 0.72^b	36.60 ± 0.51^a	36.71 ± 0.63^a
a^*	Control	-6.43 ± 0.49^a	-6.72 ± 0.61^a	-6.31 ± 0.40^b	-6.19 ± 0.68^b	-5.71 ± 0.29^a
	ε-PL	-6.88 ± 0.80^a	-6.60 ± 0.91^a	-6.62 ± 0.34^b	-5.53 ± 0.67^a	-6.11 ± 0.44^a
	ε-p-CA	-6.77 ± 0.33^a	-6.48 ± 0.35^a	-5.57 ± 0.51^a	-5.46 ± 0.25^a	-6.06 ± 0.60^a
b^*	Control	14.90 ± 0.52^a	14.27 ± 0.66^a	13.42 ± 0.60^a	12.05 ± 0.84^a	12.07 ± 0.61^a
	ε-PL	14.52 ± 0.82^a	14.72 ± 0.88^a	13.13 ± 0.84^{ab}	12.60 ± 0.73^a	12.36 ± 0.57^a
	ε-p-CA	14.46 ± 0.57^a	14.92 ± 0.74^a	12.88 ± 0.69^b	11.93 ± 0.74^a	11.94 ± 0.79^a
ΔE	Control	4.78 ± 0.47^b	5.32 ± 0.40^a	5.47 ± 0.57^b	6.48 ± 1.54^b	7.43 ± 0.16^a
	ε-PL	5.79 ± 0.64^a	5.09 ± 1.06^a	5.74 ± 0.50^b	5.37 ± 1.05^b	6.72 ± 0.49^a
	ε-p-CA	4.95 ± 0.43^b	4.69 ± 1.06^a	7.22 ± 0.55^a	7.90 ± 0.56^a	6.96 ± 0.95^a

Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

of green pepper slices did not change significantly during the entire storage period [8]. This outcome can be attributed to the degradation of chlorophyll resulting from factors such as oxygen presence and chlorophyllase enzymes. The reduction in enzyme activity at lower temperatures contributes to the delayed alteration in color [29]. Regarding the yellow-blue (b^**), the control group slightly decreased throughout the storage period, while the treatment group showed an increase followed by a decrease. However, no significant distinction was observed between the treatment and control groups on day 12 of storage ($P > 0.05$). The total color difference (ΔE) gradually increased overall. Notably, a significant rise was observed in the ε-p-CA group on the sixth day, which remained relatively stable thereafter. The ε-p-CA group had less effect on the color of the peppers, and their color remained within acceptable parameters throughout the storage period.

3.3.4. Electrolyte Leakage. Electrolyte leakage serves as a quantitative parameter that reflects the extent of cellular damage in plants and exhibits a correlation with the quality of fruits and vegetables throughout the storage duration [18]. As depicted in Figure 5(a), the electrolyte leakage was marginally higher in the ε-p-CA group (5.95 ± 0.21) % compared to the control group (5.77 ± 0.24) % at the commencement of the storage period. This discrepancy could potentially be attributed to the presence of residual substances on the surface of the peppers subsequent to the combined treatment of the two compounds, although the disparity observed was not statistically significant ($P > 0.05$).

On day 6, there was a notable increase in electrolyte leakage in the control group, reaching (8.16 ± 0.14) %, which was significantly higher compared to the ε-p-CA group, where the electrolyte leakage was (7.22 ± 0.16) %. It is manifest that the control group evinces an augmentation in cellular membrane permeability, culminating in the substantial efflux of intracellular substances, thereby hastening the deterioration of the quality of bell pepper slices. On day 12, the ε-p-CA group exhibited a 33.6% reduction in electrolyte leakage compared to the ε-PL group and a remarkable 92.8% reduction compared to the control group. This indicates that the combined treatment of the two drugs is more effective. Pintos et al. similarly reported an elevation in electrolyte leakage in fresh-cut green bell peppers as the duration of storage increased [8]. Higher values of electrolyte leakage indicate compromised cell integrity. The findings demonstrated that ε-p-CA exhibited effective inhibition of the cell membrane permeation rate in fresh-cut peppers, thereby preserving the tissue integrity of the peppers more effectively.

3.3.5. MDA Content. MDA is one of the final products of lipid peroxidation in cell membranes, possesses direct cytotoxicity, and contributes to the exacerbation of cell membrane damage. It serves as a crucial indicator for evaluating the extent of oxidative stress in green pepper samples [19]. As shown in Figure 5(b), the MDA content exhibited an upward trajectory in all three sample groups throughout the storage period, and a similar trend was observed for fresh-cut green bell peppers by Chen et al. [30]. At the onset of storage, the MDA content in all three sample groups was approximately (0.19 ± 0.015) μmoL/g. On day 3, there was a substantial surge in the MDA content of the control group to (0.36 ± 0.015) μmoL/g, which exhibited a significant disparity when compared to the ε-p-CA group's MDA content of (0.27 ± 0.013) μmoL/g ($P < 0.05$). In the cross-section of freshly sliced green peppers, the accumulation of free radicals and reactive oxygen species leads to the escalating oxidation of cellular membrane lipids. On day 9, there was a notable escalation in MDA levels within the ε-PL group, displaying a significant distinction from the ε-p-CA group ($P < 0.05$). On day 12 of the storage period, the MDA content in the control group surged to (0.98 ± 0.02) μmoL/g, indicative of severe peroxidative damage to cell membrane lipids. In contrast, the ε-PL and ε-p-CA groups exhibited MDA contents of (0.58 ± 0.018) μmoL/g and (0.39 ± 0.011) μmoL/g. In comparison to the ε-p-CA group, the MDA content in the control group was 2.5 times higher, while in the ε-PL group, it was 1.49 times higher. Increased MDA content is also linked to the impairment of membrane

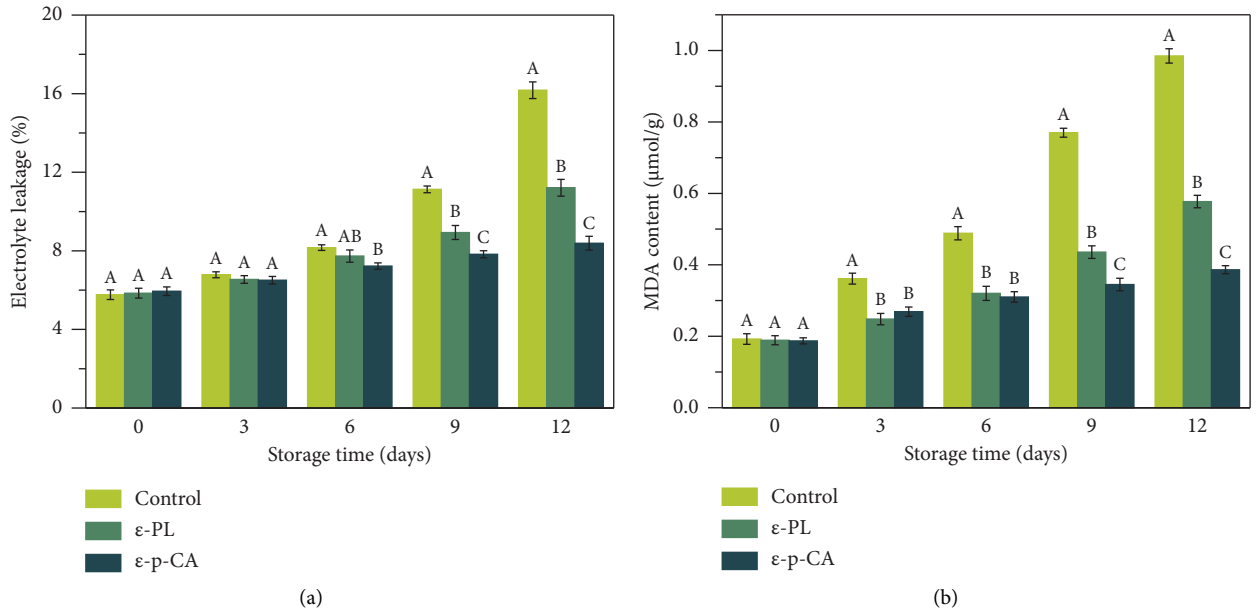

FIGURE 5: During a 12-day storage period at 8°C, electrolyte leakage (a) and MDA content (b) changes in green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid. Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

permeability and the accumulation of reactive oxygen species [15]. These findings suggested that the synergistic application of ε-p-CA could effectively suppress the buildup of MDA and mitigate the extent of membrane peroxidation damage in green bell pepper fruits throughout the storage period.

3.3.6. Respiratory Rate. Respiration rate, as an indicator of metabolic activity, reflects changes in the physiological metabolism of the sample [31]. As depicted in Figure 6(a), the respiration rate of the three groups of samples exhibited a progressive elevation throughout the storage period. This effect can be attributed to the induced stress resulting from the mechanical injury incurred during the cutting process, which subsequently triggers an accelerated respiratory activity in fresh-cut peppers [30]. Respiratory rates were generally consistent between control and treated groups during the initial day 0 of storage. However, commencing from day 6, there was a sharp increase in respiratory rate in the control group and a mild increase in the ε-p-CA group. On day 12 of storage, there was a substantial surge of 163% in the respiration rate of the control group, accompanied by a 140% increase in the ε-PL group, both in comparison to the initial storage period. In contrast, the ε-p-CA group exhibited a noteworthy reduction of 56.4% compared to the control group. The findings suggested that ε-p-CA has a significant impact on modulating the respiration rate in fresh-cut peppers, leading to a reduction in oxidative metabolism. Simultaneously, the application of ε-PL and p-CA on the surface of chili exhibits a significant inhibitory effect on microbial respiration and cellular metabolism, retarding microbial intrusion into the pepper slices and preserving tissue integrity [11].

3.3.7. Ethylene Content. Fresh-cutting procedures induce the generation of wound ethylene, and wound ethylene can accelerate the ripening and aging of fruits and vegetables [32]. Figure 6(b) illustrates the variations in ethylene content in fresh-cut green bell pepper throughout the 12-day storage duration. During the initial day 6 of storage, both the treated and control groups displayed a moderate increase in ethylene content, and there was no significant difference observed between them ($P < 0.05$). On day 9, there was a substantial rise in ethylene content across all three groups, with the control group exhibiting (12.79 ± 0.70) μL/kg/h, the ε-PL group displaying (10.82 ± 0.69) μL/kg/h, and the ε-p-CA group demonstrating the lowest level at (9.84 ± 0.70) μL/kg/h. On the 12th day of storage, the ethylene content of the control group exhibited a significant increase to (18.95 ± 0.61) μL/kg/h, which was 4.76 μL/kg/h higher than that of the ε-PL group and 6.23 μL/kg/h higher than that of the ε-p-CA group. These findings indicate that the treatment of fresh-cut peppers with ε-p-CA effectively suppresses ethylene production, leading to better preservation of the quality of fresh-cut peppers. This may be attributed to the effective suppression of the metabolic activity of ethylene synthase by ε-p-CA, resulting in restricted ethylene biosynthesis pathways [33].

3.3.8. DPPH Scavenging Activity. Free radicals within cells induce harm and disruption to macromolecules such as nucleic acids and proteins, while the accumulation of free radicals promotes membrane lipid oxidation and hastens cellular senescence [34]. As depicted in Figure 7(a), prior to the commencement of storage, the control, ε-PL, and ε-p-CA groups exhibited free radical scavenging capacities of 83.20 ±

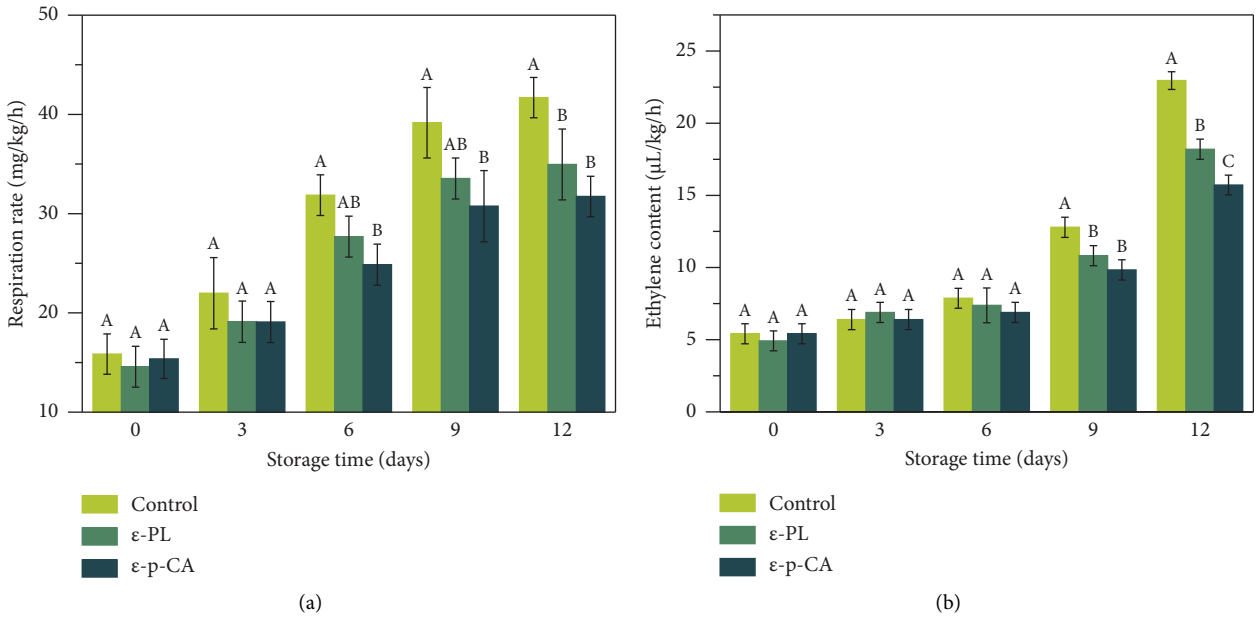

FIGURE 6: During a 12-day storage period at 8°C, respiratory rate (a) and ethylene content (b) changes in green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid. Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

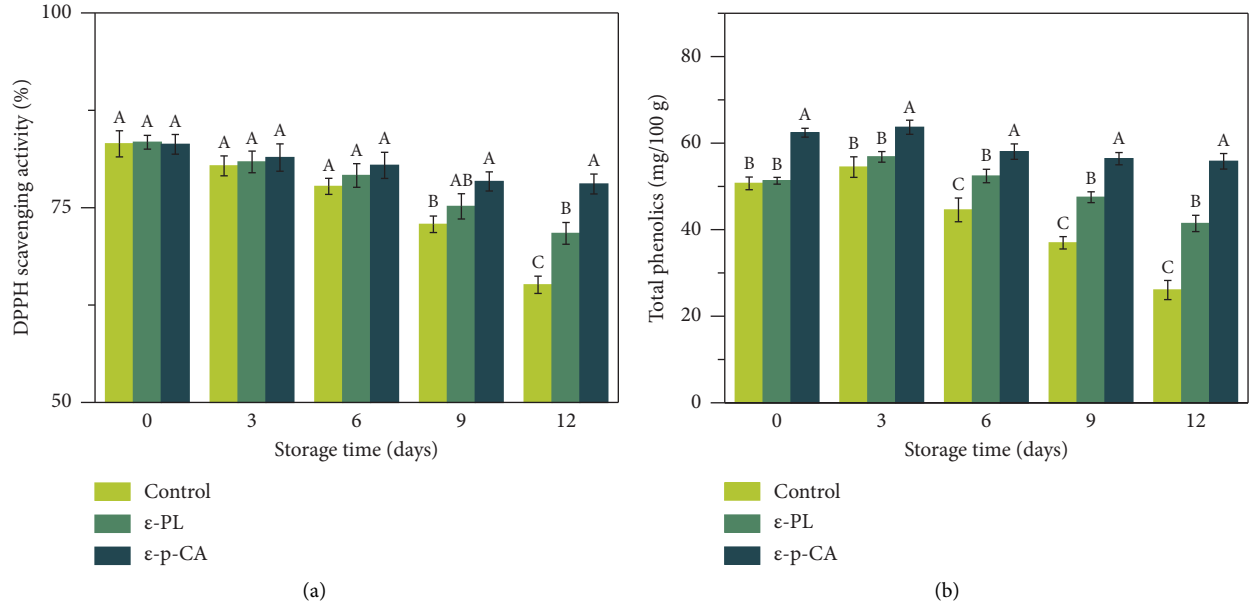

FIGURE 7: During a 12-day storage period at 8°C, DPPH scavenging activity (a) and total phenolics (b) changes in green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid. Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

1.67%, 83.40 ± 0.88%, and 83.13 ± 1.29%, respectively, with no statistically significant disparity observed among the three groups. Nevertheless, on day 9, the free radical scavenging capacity of the control group exhibited a rapid decline and displayed a significant disparity compared to the ε-p-CA group. On day 12 of the storage period, the ε-p-CA group maintained a notably high free radical scavenging capacity of 78.03%, whereas the free radical scavenging capacity of the ε-PL group decreased to 71.70%, and that of the control group reached a mere 65.10%. This phenomenon can be attributed to the interaction between p-CA and the free radical (R^*), leading to the transfer of a hydrogen atom from p-CA to the free radical by disrupting the O-H bond. Consequently, this process stabilizes or deactivates the free radical, resulting in the maintenance of a high free radical scavenging capacity within the sample [35].

3.3.9. TPC. Phenolic compounds, as significant antioxidant constituents, possess numerous functional and active effects on the quality attributes of fruits and vegetables [3]. The TPC of the ε-p-CA group was significantly higher than the other two groups at the beginning of storage, owing to the inclusion of p-CA (Figure 7(b)). On day 3 of storage, the TPC experienced a general increase and reached its maximum level in all three sample groups, followed by a subsequent decline. These changes are mainly due to the mechanical damage caused by cutting green pepper, which cause an increase in phenylalanine aminolysis enzyme activity, which contributes to a significant accumulation of phenolics [36]. Starting from day 6, the TPC of the ε-p-CA group exhibited stability, whereas the control and ε-PL groups demonstrated a declining pattern. On day 12, the ε-p-CA group maintained a TPC of (55.80 ± 1.79) mg/100 g, the ε-PL group had (41.43 ± 1.88) mg/100 g, and the control group displayed a significantly lower content of (26.07 ± 2.21) mg/100 g ($P < 0.05$). These results indicated that the ε-p-CA treatment effectively preserved a higher TPC in fresh-cut green bell peppers.

3.4. Nutritional Composition

3.4.1. SSC. The alterations in the soluble sugar content of green bell pepper slices are depicted in Figure 8(a). During the initial stages of storage, there was no significant disparity in soluble sugar content between the control and experimental groups. However, on day 6, the soluble sugar content in the control group reached its zenith at (2.99 ± 0.05) g/100 g, displaying a pronounced differentiation from the experimental group. Over the course of time, the soluble sugar content in the control group commenced a decline, while the ε-PL group, after attaining its peak on day 9 at (2.98 ± 0.08) g/100 g, also embarked on a descending trajectory. This phenomenon could potentially be attributed to the environmental stress experienced during the storage of fresh-cut bell peppers, which triggers the breakdown of endogenous macromolecules, particularly proteins. This process leads to an increased production of soluble sugars [37]. However, as the storage duration progressed, the substantial depletion of soluble sugars was observed, attributable to the accelerated respiration rate and heightened electrolyte leakage. It is noteworthy that the ε-p-CA group did not show a decrease in soluble sugar content at the later stages of storage. This observation can be attributed to the combined treatment of the ε-PL and p-CA, which exhibited a retarding effect on the activity of cellular metabolic enzymes. This effect was closely associated with a lower respiration rate and a reduction in electrolyte leakage [38].

3.4.2. Vc Content. The assessment of Vc content stands as a pivotal criterion for appraising the quality of freshly cut green bell peppers. Green bell peppers, favored by consumers for their elevated Vc content, are nonetheless susceptible to oxidation in the presence of oxygen [1]. Consequently, Vc content serves as an indicator of the degree of oxidation in freshly cut green bell peppers. As illustrated in Figure 8(b), throughout the entire storage period, the Vc content in the ε-p-CA group exhibits a gradual descent, while the control group experiences a more rapid decline. The ε-p-CA group displays the most minimal Vc loss at a mere 12.41%, in contrast to the ε-PL group at 17.36% and the control group at 32.23%. The decline in Vc content not only profoundly impacts the nutritional composition of green pepper slices but also indirectly signifies a weakening of their inherent defensive capabilities. This is similar to the trend of Vc content measured in fresh-cut kiwifruit treated by high-intensity sonication in Yıldız [39]. In the initial phase of storage, the Vc levels among the three groups measured (82.40 ± 1.12) mg/100 g, with no conspicuous disparities. On day 6, the Vc content in the control group swiftly declined, displaying a significant contrast when compared to the ε-p-CA group. On day 12 arrived, the ε-p-CA group continued to maintain a certain level of Vc content at (72.21 ± 1.66) mg/100 g, while the control group had only (55.86 ± 1.19) mg/100 g. The research outcomes signify that ε-p-CA effectively curbs the depletion of Vc in freshly cut green peppers.

3.5. Microbiological Analysis

3.5.1. Aerobic Bacteria. In this study, the alterations in the population of aerobic bacteria in freshly cut green bell pepper samples are depicted in Figure 9(a). At the onset of storage, the aerobic bacterial plate count stood at (3.36 ± 0.1) log CFU/g, signifying the exceptional quality of the samples. Following the combined treatment with ε-PL and ε-p-CA, no noticeable alterations in bacterial counts were observed immediately, and all three sample groups showed a gradual increase in aerobic bacterial counts throughout the storage period. The control group increased sharply from day 6, reaching (4.88 ± 0.05) log CFU/g, whereas the ε-PL and ε-p-CA groups demonstrated a slower increase at (4.25 ± 0.01) log CFU/g and (4.11 ± 0.03) log CFU/g, respectively. This finding is consistent with the results reported by Ranjitha, who observed that the microbial population in freshly cut green bell peppers remained within acceptable limits during storage at 8°C for day 6 [40]. On day 9, the aerobic bacterial count was (6.04 ± 0.04) log CFU/g in the control group, while the ε-PL and ε-p-CA groups had counts of (4.91 ± 0.04) log CFU/g and (4.73 ± 0.07) log CFU/g, respectively. It is worth noting that a limit of 5.0 log CFU/g is commonly used as a tolerance level for evaluating the microbiological quality of ready-to-eat or ready-to-eat fresh-cut green peppers [15]. Figure 3, the images of fresh-cut green pepper samples from different treatment groups during storage also visually reflect the increase in the total number of microorganisms. The results demonstrated that the treatment with ε-PL and ε-p-CA exhibited significant inhibitory effects on the growth and proliferation of aerobic bacteria, resulting in an extended shelf life for fresh-cut green peppers.

3.5.2. Molds and Yeasts. The preservation effect of ε-PL and p-CA treatments on fresh-cut green bell peppers was investigated by quantifying mold and yeast populations (Figure 9(b)). The initial mold and yeast counts in the control group were (3.36 ± 0.04) log CFU/g, which did not exhibit a significant difference when compared to the ε-PL group (3.41 ± 0.06) log CFU/g and the ε-p-CA group

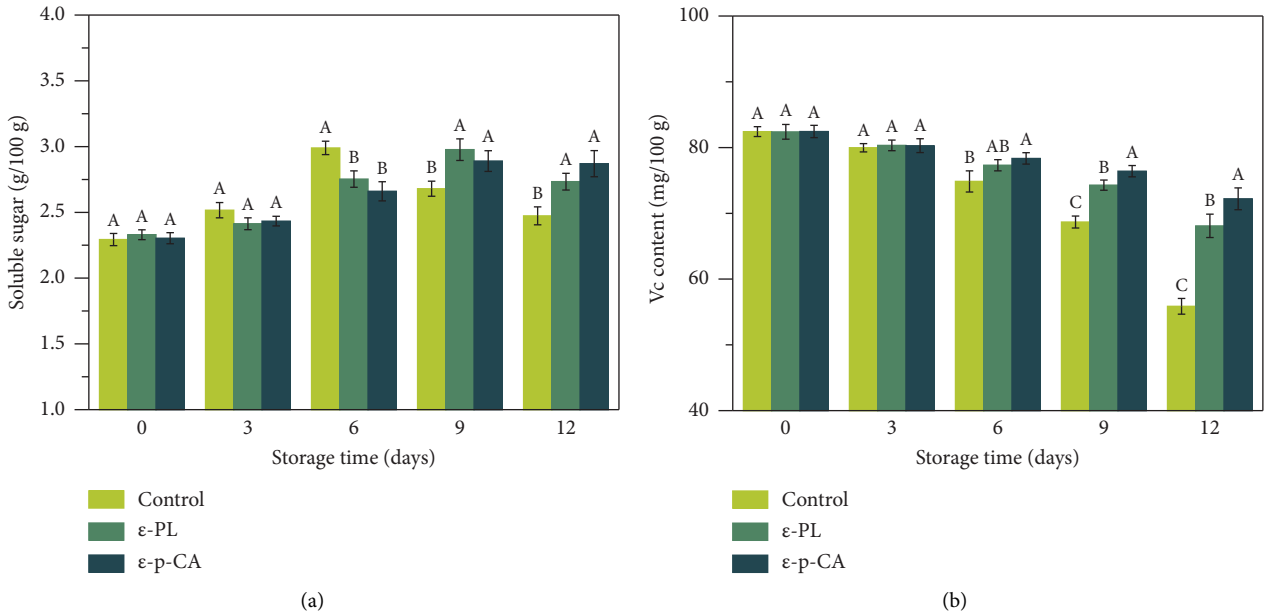

Figure 8: During a 12-day storage period at 8°C, soluble sugar (a) and Vc content (b) changes in green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid. Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

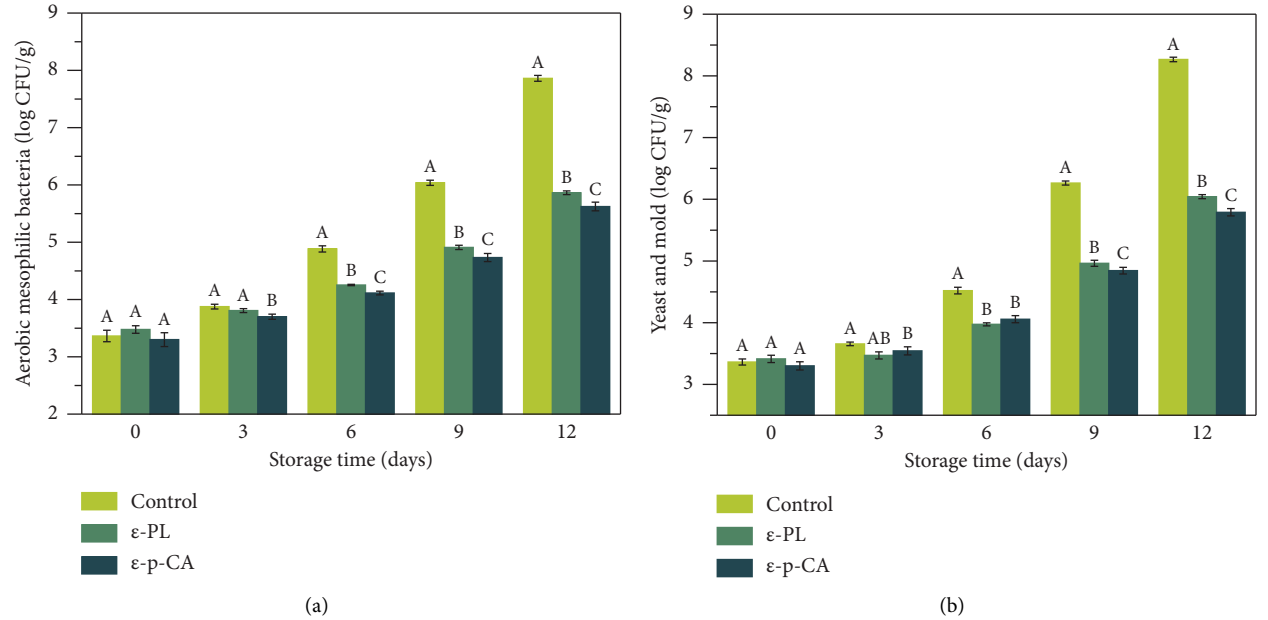

Figure 9: During a 12-day storage period at 8°C, aerobic bacteria (a) and molds and yeasts (b) changes in green bell pepper slices treated with ε-polylysine alone and in combination with p-Coumaric acid. Vertical bars show the standard error of the means and different letters at the same storage time are significantly different at $P < 0.05$.

(3.30 ± 0.07) log CFU/g ($P > 0.05$). As the storage time progressed, the control group exhibited a sharp increase on day 9, whereas the ε-PL and ε-p-CA groups displayed a moderate increase throughout the storage period. At the end of the day 12 storage period, the mold and yeast counts reached (8.27 ± 0.03) log CFU/g in the control group, whereas in the ε-PL group and ε-p-CA group, they were (6.04 ± 0.06) log CFU/g and (5.79 ± 0.06) log CFU/g, respectively. The results suggested that ε-PL and p-CA exhibiting significantly lower mold and yeast counts compared to the control group. These findings are consistent with the microbial indicators observed by Pintos et al., who applied riboflavin treatment to fresh-cut green peppers [8].

4. Conclusion

This study investigated the combined effects of ε-polylysine (ε-PL) and p-Coumaric acid (p-CA) on the preservation of fresh-cut green bell peppers. Through experiments, the optimal concentration of ε-PL was determined to be 25 mg/L, while a concentration of 10 mg/L of p-CA significantly reduced decay and improved preservation effectiveness. Various physical, chemical, and microbiological properties of the peppers were evaluated during a 12-day storage period. The results demonstrated that the application of ε-p-CA effectively reduced the decay rate of fresh-cut green bell peppers and minimized weight loss throughout the storage period, thereby maintaining the peppers' hardness. Moreover, it efficiently inhibited electrolyte leakage and MDA content, suppressing respiration rate and ethylene production associated with aging and deterioration. In terms of nutritional components, ε-p-CA treatments preserved the Vc content and inhibited soluble sugar loss. In addition, they increased the TPC, contributing to antioxidant activity. Microbiological analysis indicated that the combined treatment significantly reduced the populations of aerobic bacteria, molds, and yeasts, suggesting antibacterial properties. In conclusion, the combined treatment of ε-p-CA exhibited favorable effects on maintaining the quality and extending the shelf life of fresh-cut green peppers. Further research is required to fully understand the potential mechanisms of this preservation method and its potential application in other fresh-cut agricultural products.

Data Availability

All data generated or analyzed during this study are included in this published article.

Additional Points

Highlights. (1) Fresh-cut fruits and vegetables are susceptible to rapid deterioration, leading to shortened shelf life. (2) Conventional methods for preserving fruits and vegetables involve the use of chemical preservatives, their effectiveness is limited due to concerns related to food safety, environmental impact, and preservation efficacy. Meanwhile, implementing physical preservation techniques often involves substantial expenses and presents hurdles in promotion and widespread adoption. (3) ε-polylysine demonstrates inherent antibacterial properties and exhibits potent antioxidant activity for p-Coumaric acid. (4) The present study proposes a novel, convenient, and eco-friendly preservation method for fresh-cut green peppers, wherein the combined effects of ε-polylysine and p-Coumaric acid are utilized. In order to provide an application reference for the large-scale production of fresh-cut agricultural products.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Youwei Yu conceptualized the study, wrote the original draft, and provided funding acquisition. Jianfu Qiao performed investigation, contributed to data curation, and wrote the original draft. Shaoying Zhang performed investigation, contributed to data curation, and validated the study. Haochen Li contributed to the methodology and wrote, reviewed, and edited the manuscript. Shaoze Huang and Ying Qin performed investigation and contributed to data curation.

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References

[1] J. Chen, M. Zheng, K. B. Tan, J. Lin, M. Chen, and Y. Zhu, "Development of xanthan gum/hydroxypropyl methyl cellulose composite films incorporating tea polyphenol and its application on fresh-cut green bell peppers preservation," *International Journal of Biological Macromolecules*, vol. 211, pp. 198–206, 2022.

[2] H. E. Salama and M. S. Abdel Aziz, "Development of active edible coating of alginate and aloe vera enriched with frankincense oil for retarding the senescence of green capsicums," *LWT-Food Science and Technology*, vol. 145, no. 16, Article ID 111341, 2021.

[3] I. Nicolau-Lapeña, I. Aguiló-Aguayo, B. Kramer, M. Abadias, I. Viñas, and P. Muranyi, "Combination of ferulic acid with Aloe vera gel or alginate coatings for shelf-life prolongation of fresh-cut apples," *Food Packaging and Shelf Life*, vol. 27, no. 3, Article ID 100620, 2021.

[4] M. A. Perito, E. Chiodo, A. Serio, A. Paparella, and A. Fantini, "Factors influencing consumers' attitude towards biopreservatives," *Sustainability*, vol. 12, no. 24, Article ID 10338, 2020.

[5] X. Meng, M. Zhang, Z. Zhan, and B. Adhikari, "Changes in quality characteristics of fresh-cut cucumbers as affected by pressurized argon treatment," *Food and Bioprocess Technology*, vol. 7, no. 3, pp. 693–701, 2014.

[6] M. I. Elias, J. Madureira, P. M. P. Santos, M. M. Carolino, F. M. A. Margaca, and S. C. Verde, "Preservation treatment of fresh raspberries by e-beam irradiation," *Innovative Food Science and Emerging Technologies*, vol. 66, 2020.

[7] X. Zhang, W. Meng, Y. Chen, and Y. Peng, "Browning inhibition of plant extracts on fresh-cut fruits and vegetables—a review," *Journal of Food Processing and Preservation*, vol. 46, no. 5, p. 46, 2022.

[8] F. M. Pintos, M. L. Lemoine, G. Gergoff Grozeff, H. Hasperué, A. R. Vicente, and L. M. Rodoni, "Use of riboflavin to reduce decay and extend the shelf-life of fresh-cut sweet pepper," *Postharvest Biology and Technology*, vol. 188, Article ID 111882, 2022.

[9] S. Ali, A. S. Khan, and A. U. Malik, "Postharvest l-cysteine application delayed pericarp browning, suppressed lipid peroxidation and maintained antioxidative activities of litchi fruit," *Postharvest Biology and Technology*, vol. 121, pp. 135–142, 2016.

[10] H. Zhang, Y. Zheng, and R. Li, "Effects of chitosan-based coatings incorporated with ε-polylysine and ascorbic acid on the shelf-life of pork," *Food Chemistry*, vol. 390, Article ID 133206, 2022.

[11] W. Lan, N. Zhang, S. Liu, M. Chen, and J. Xie, "ε-Polylysine inhibits Shewanella putrefaciens with membrane disruption and cell damage," *Molecules*, vol. 24, no. 20, p. 3727, 2019.

[12] A. Venkatesan, J. V. R. A. Samy, K. Balakrishnan, V. Natesan, and S.-J. Kim, "In vitro antioxidant, anti-inflammatory, antimicrobial, and antidiabetic activities of synthesized chitosan-loaded p-Coumaric acid nanoparticles," *Current Pharmaceutical Biotechnology*, vol. 24, no. 9, pp. 1178–1194, 2023.

[13] S. Roychoudhury, B. Sinha, B. P. Choudhury et al., "Scavenging properties of plant-derived natural biomolecule para-coumaric acid in the prevention of oxidative stress-induced diseases," *Antioxidants*, vol. 10, no. 8, p. 1205, 2021.

[14] I. Kiliç and Y. Yeşiloğlu, "Spectroscopic studies on the antioxidant activity of p-coumaric acid," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 115, pp. 719–724, 2013.

[15] H.-Z. Chen, M. Zhang, B. Bhandari, and Z. Guo, "Evaluation of the freshness of fresh-cut green bell pepper (Capsicum annuum var. grossum) using electronic nose," *LWT-Food Science and Technology*, vol. 87, pp. 77–84, 2018.

[16] M. Ma, Z. Zhu, S. Cheng et al., "Methyl jasmonate alleviates chilling injury by regulating membrane lipid composition in green bell pepper," *Scientia Horticulturae*, vol. 266, Article ID 109308, 2020.

[17] G. Yildiz, S. Palma, and H. Feng, "Ultrasonic cutting as a new method to produce fresh-cut red delicious and golden delicious apples," *Journal of Food Science*, vol. 84, no. 12, pp. 3391–3398, 2019.

[18] S. Ali, A. S. Khan, M. A. Anjum et al., "Aloe vera gel coating delays post-cut surface browning and maintains quality of cold stored lotus (*Nelumbo nucifera* Gaertn.) root slices," *Scientia Horticulturae*, vol. 256, Article ID 108612, 2019.

[19] D. Xu, S. M. Lam, J. Zuo et al., "Lipidomics reveals the difference of membrane lipid catabolism between chilling injury sensitive and non-sensitive green bell pepper in response to chilling," *Postharvest Biology and Technology*, vol. 182, Article ID 111714, 2021.

[20] K. Prasad, R. R. Sharma, R. Asrey et al., "Hydrocolloid edible coatings extend shelf life, reduce postharvest decay, and maintain keeping quality of mango fruits (Mangifera indica L.) under ambient storage," *Journal of Food Biochemistry*, vol. 46, no. 12, Article ID e14481, 2022.

[21] G. Yildiz and R. M. Aadil, "Comparative analysis of anti-browning agents, hot water and high-intensity ultrasound treatments to maintain the quality of fresh-cut mangoes," *Journal of Food Science and Technology*, vol. 59, pp. 202–211, 2022.

[22] S. Wu, "Extending shelf-life of fresh-cut potato with cactus Opuntia dillenii polysaccharide-based edible coatings," *International Journal of Biological Macromolecules*, vol. 130, pp. 640–644, 2019.

[23] R. Singh, S. Giri, and N. Kotwaliwale, "Shelf-life enhancement of green bell pepper (Capsicum annuum L.) under active modified atmosphere storage," *Food Packaging and Shelf Life*, vol. 1, no. 2, pp. 101–112, 2014.

[24] National Standard of the People's Republic of China, *Food microbiological examination: aerobic plate count*, National Standard of the People's Republic of China, Beijing, China, 2010.

[25] H.-Q. Ning, Y.-Q. Li, H. Lin, and J.-X. Wang, "Apoptosis-induction effect of ε-poly-lysine against *Staphylococcus aureus* and its application on pasteurized milk," *Lebensmittel-Wissenschaft und-Technologie*, vol. 137, Article ID 110493, 2021.

[26] G. Yildiz, G. Izli, and R. M. Aadil, "Comparison of chemical, physical, and ultrasound treatments on the shelf life of fresh-cut quince fruit (Cydonia oblonga Mill.)," *Journal of Food Processing and Preservation*, vol. 44, no. 3, Article ID e14366, 2020.

[27] J. Kaur and R. Kaur, "p-Coumaric acid: a naturally occurring chemical with potential therapeutic applications," *Current Organic Chemistry*, vol. 26, no. 14, pp. 1333–1349, 2022.

[28] H. Cheng, Z. Mou, W. Wang et al., "Chitosan–catechin coating as an antifungal and preservable agent for postharvest satsuma oranges," *Journal of Food Biochemistry*, vol. 43, no. 4, Article ID e12779, 2019.

[29] S. Hedayati and M. Niakousari, "Effect of Coatings of Silver Nanoparticles and G um A rabic on Physicochemical and Microbial Properties of Green Bell Pepper (C apsicum annuum)," *Journal of Food Processing and Preservation*, vol. 39, no. 6, pp. 2001–2007, 2015.

[30] J. Chen, Y. Hu, J. Wang, H. Hu, and H. Cui, "Combined effect of ozone treatment and modified atmosphere packaging on antioxidant defense system of fresh-cut green peppers," *Journal of Food Processing and Preservation*, vol. 40, no. 5, pp. 1145–1150, 2016.

[31] L. Zhang, S. Li, Y. Dong, H. Zhi, and W. Zong, "Tea polyphenols incorporated into alginate-based edible coating for quality maintenance of Chinese winter jujube under ambient temperature," *Lwt*, vol. 70, pp. 155–161, 2016.

[32] J. K. Brecht, "Physiology of lightly processed fruits and vegetables," *HortScience*, vol. 30, no. 1, pp. 18–22, 1995.

[33] Z. Wu, M. Zhang, and S. Wang, "Effects of high pressure argon treatments on the quality of fresh-cut apples at cold storage," *Food Control*, vol. 23, no. 1, pp. 120–127, 2012.

[34] S. S. Gill and N. Tuteja, "Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants," *Plant Physiology and Biochemistry*, vol. 48, no. 12, pp. 909–930, 2010.

[35] I. Gutiérrez-del-Río, S. López-Ibáñez, P. Magadán-Corpas et al., "Terpenoids and polyphenols as natural antioxidant agents in food preservation," *Antioxidants*, vol. 10, no. 8, p. 1264, 2021.

[36] S. C. Sgroppo and M. V. Pereyra, "Using mild heat treatment to improve the bioactive related compounds on fresh-cut green bell peppers," *International Journal of Food Science and Technology*, vol. 44, no. 9, pp. 1793–1801, 2009.

[37] Y. Zhao, J. Geng, Y. Zhang, K. Nam, Z. Xue, and X. Kou, "Changes in sugar metabolism and fruit quality of different pear cultivars during cold storage," *Transactions of Tianjin University*, vol. 25, no. 4, pp. 389–399, 2019.

[38] D. Zhou, Q. Zhang, C. Wu, T. Li, and K. Tu, "Change of soluble sugars, free and glycosidically bound volatile compounds in postharvest cantaloupe fruit response to cutting procedure and storage," *Scientia Horticulturae*, vol. 295, Article ID 110863, 2022.

[39] G. Yıldız, G. Yildiz, M. R. Khan, and R. M. Aadil, "High-intensity ultrasound treatment to produce and preserve the quality of fresh-cut kiwifruit," *Journal of Food Processing and Preservation*, vol. 46, no. 5, Article ID e16542, 2022.

[40] K. Ranjitha, D. Sudhakar Rao, K. Shivashankara, and T. K. Roy, "Effect of pretreatments and modified atmosphere packaging on the shelf life and quality of fresh-cut green bell pepper," *Journal of Food Science and Technology*, vol. 52, no. 12, pp. 7872–7882, 2015.