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Application of Cinnamaldehyde Solid Lipid Nanoparticles in Strawberry Preservation

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Abstract: Strawberries are a popular food. However, the growth and reproduction of microorganisms on the surface of strawberries change their quality and may cause food poisoning. We compared the effects of solid lipid nanoparticles containing cinnamaldehyde (SLN-CA) and unencapsulated cinnamaldehyde on the freshness of strawberries stored for seven days. The impacts of SLN-CA at different concentrations on strawberry firmness, weight loss, rate of fruit rot, and sensory quality were investigated at 25 °C. Superoxide dismutase (*SOD*) and catalase activities and malonaldehyde (*MDA*) and vitamin C contents of strawberry cell homogenates were measured during storage. The experimental results showed that SLN-CA treatment can effectively reduce the probability of decay in strawberries without causing excessive weight loss. SLN-CA can reduce softening, maintain a high level of *SOD* activity in cells, reduce the accumulation of *MDA* and consumption of organic acids, and improve the sensory characteristics of strawberries and thereby their shelf life. Therefore, SLN-CA is a promising preservation method to increase the shelf life and safety of strawberries.

Keywords: postharvest; solid lipid nanoparticles; *Fragaria*; fruit storage

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1. Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) belongs to the family Rosaceae. The fruit is deliciously sweet, aromatic, and red in colour and has a unique flavour. The pulp is rich in dietary fibres and minerals, whereas the skin is rich in anthocyanins and contains many biologically active components, including polyphenolic compounds, flavonoids, vitamins, pectin, and organic acids, which are highly nutritious [1–5]. Strawberries do not have strong skin, and the cell wall strength is relatively low, which easily causes mechanical damage during production and transportation. Mechanical damage causes damage to the exterior of the strawberry, resulting in the leakage of cellular fluid. The cytosol contains a large amount of nutrients that greatly facilitate the infection and growth of microorganisms. The microorganisms' growth is the main cause of post-harvest rot and spoilage in strawberries [6–8]. In addition, fresh strawberries have high respiration and fast metabolic rates, which further accelerate fruit decay [7]. Mildew, softening, and rotting of strawberries can have serious adverse effects during storage, transportation, and sale [9,10]. Therefore, strawberries are considered a fragile commodity with a very limited shelf life, typically 6–9 days at 25 °C, and an estimated loss rate of up to 40% from the harvest and storage to table process [11]. Rapid cooling after picking and storing strawberries at a low temperature of 0–4 °C is an effective and common method to maintain the fruit quality. [12]. However, the process of an unbroken cold chain, from picking to the supermarket, is cost-intensive in terms of material and personnel [13].

Cinnamaldehyde (CA), the main component of essential oils extracted from natural cinnamon plants, has good antibacterial activity (MIC:1.88 mM) [14]. CA has been found to inhibit the growth of various bacteria, such as *Escherichia coli*, *Salmonella*, *Bacillus subtilis*, and

Pseudomonas aeruginosa. CA has been recognised as "Generally Recognized as Safe" (GRAS) by the US Food and Drug Administration (FDA) and Flavor and Extract Manufacturers Association. Additionally, the European Commission allows the use of CAs in food. [15]. CA is a natural, green, safe, and highly sensitive antibacterial preservative with great development potential and good application prospects in the food industry [16,17]. The application of these natural compounds in the food industry may be a potential alternative; however, the cost of their application and other issues such as their strong flavour and potential toxicity limit their use in food conservation [18].

Owing to its pungent odour, CA is difficult to apply directly to fruits and vegetables. Moreover, a high concentration of CA has a burning effect on the surface of products and shortens their shelf life. Additionally, high volatilisation and poor stability of CA reduce its long-term antibacterial effects. A practical solution to overcome these limitations is to encapsulate CA in solid lipid nanoparticles to form a nanocomplex.

Superoxide dismutase (*SOD*) and catalase (CAT) are important antioxidant enzymes in plant cells [19], which eliminate harmful free radicals both inside and outside the cells, maintain cellular metabolic homeostasis, and protect cells from oxidative damage [20]. *SOD* primarily clears superoxide free radicals produced within cells, whereas CAT clears hydrogen peroxide molecules inside and outside the cells. Together, they maintain the oxidation-reduction balance within the cells and protect strawberry cells from oxidative damage. Malonaldehyde (*MDA*) is a toxic metabolite primarily used as a marker of oxidative stress to measure the degree of oxidative damage to biological molecules such as cell membranes and enzymes [21].

Solid lipid nanoparticles (SLN) are nanoscale drug carriers developed in the 1980s and 1990s [22]. SLN typically consist of three fundamental components: solid lipids, surfactants, and water. Lipid compounds are generally recognised as safe (GRAS) and have been shown to possess biocompatibility and biodegradability since they are naturally present in living organisms. Solid lipid nanoparticles can encapsulate drugs, thereby protecting them from degradation [23], decomposition, or inactivation. Sustained drug release can be achieved by adjusting factors such as the particle size, composition, and surface structure [24]. Owing to the high stability, simple preparation, high drug loading, excellent biocompatibility, and biodegradability of SLN, they are one of the current research hotspots [25].

Therefore, the aim of this study was to investigate the effect of solid lipid nanoparticles containing cinnamaldehyde (SLN-CA) on postharvest strawberry preservation and to evaluate fruit firmness, colour, *SOD*, *MDA*, CAT, cell membrane integrity, and sensory evaluation results after SLC-CA treatment to provide efficient, long-lasting, natural, and pollution-free preservatives for future agricultural and horticultural industries.

2. Materials and Methods

2.1. Strawberry

Strawberries (cultivar Sweet Charlie) were harvested in December from a strawberry garden in the Jinwan District of Zhuhai City, Guangdong Province, China. Strawberries of similar size, maturity, and shapes, with no mechanical damage, weighing 18–22 g, and with approximately 80% red fruit surface were selected. Fresh strawberries were immediately sent to the laboratory at the School of Pharmacy and Food Science, Zhuhai Institute of Science and Technology, Jinwan District, Zhuhai, China. The experiment started when the samples arrived at the laboratory and lasted for seven days.

2.2. Preparation of SLN-CA

SLN-CA was prepared by ultrahigh-pressure homogenisation (UHPH) [26]. Ultrapure water was stirred on a magnetic stirrer at 65 °C, and 1.5% (*w*/*v*) Poloxamer 188 (BR, CAS: 9003-11-6, Shanghai Yuanye Bio-Technology Co., Ltd., Shanghai, China) and 1.5% (*w*/*v*) Lecithin High Potency (Shengqing Bio Ltd., Xi'an, China) were added as the aqueous phase. We added 1.5% (*w*/*v*) Tween-80 (PC, CAS: 9005-65-6, Shanghai Yuanye BioTechnology Co., Ltd., Shanghai, China), 1.5% (*w*/*v*) monostearin (PC, CAS: 9005-65-6,

Shanghai Yuanye BioTechnology Co., Ltd., Shanghai, China), and 4% (*v*/*v*) CA (AR, 95%, CAS: 104-55-2, Shanghai Yuanye Biotechnology Co., Ltd., Shanghai, China) to the oil phase and stirred using a magnetic stirrer at 65 °C. The aqueous phase was gradually added to the oil phase under constant stirring, followed by emulsification and homogenisation using a microfluidizer. Finally, the homogenised nanoemulsion was rapidly cooled and solidified into nanoparticles.

2.3. Handling Strawberries and Preservation

To evaluate the quality of strawberries, 240 strawberries were divided into eight groups for weight loss experiments. Additionally, 672 strawberries were randomly divided into eight groups, out of which seven groups underwent treatment with different concentrations of SLN-CA (16.6, 8.3, 4.6, 2.08, and 1.04 μL/mL), CA (6.6 and 1.04 μL/mL), and ultrapure water. For each treatment, 84 fruits were placed in a large storage box.

2.4. Decay Index of Strawberry Spoilage

The freshness preservation ability of the SLN-CA solution for strawberries was evaluated by analysing the decay incidence and severity during postharvest storage of fruits [27]. Sixty strawberries were selected from the treated pile and divided into three groups, and the occurrence and severity of spoilage in each group were recorded daily for seven consecutive days.

The decay index was graded into 5 levels. (0 = absence of symptoms; 1 = 1–25% of injured area; 2 = 26–50%; 3 = 51–75%; and 4 = 76–100%) [28].

$$X = \frac{n_1 + n_2 + n_3 + n_4}{n} \times 100$$

$$S = \frac{1n_1 + 2n_2 + 3n_3 + 4n_4}{4n} \times 100$$

where X is Corruption rate (%); S is Severity (%); n_1–n_4 are the number of strawberries in decay classes 1–4; n is the total number of strawberries evaluated in each replicate experiment.

2.5. Quality Evaluation

2.5.1. Weight Loss

The weight loss of each fruit during storage was determined by daily weighing and expressed as a percentage of weight loss relative to the initial weight according to the following formula:

$$\mathrm{W} = \frac{(m_0 - m_n)}{m_0} \times 100\%$$

where W is the weight loss rate (%) of the strawberry samples; m_0 is the weight of the strawberries before storage, and m_n is the weight on day n.

2.5.2. Firmness

Firmness was measured using a texture analyser (Bosin, TA. TOUCH, Shanghai, China) with a 6 mm cylindrical probe and mode selection: texture profile analysis. The test was conducted at a pre-test speed of 2 mm/s, test speed of 1 mm/s, and post-test speed of 1 mm/s. The target mode was set to a displacement (mm) value of 5 mm. Each experimental group was further divided into five parallel groups. Changes in skin and flesh firmness after treatment with preservation liquid during storage were analysed.

2.5.3. Colour Variation and Visual Appearance

After seven days of storage, the strawberries were removed from the storage environment and equilibrated at room temperature. Colour was measured at 25 °C using a colorimeter (KONICA MINOLTA, CR-10 Plus, Tokyo, Japan). Brightness (ΔL*) and

colour saturation (Chroma, ΔC*) were selected for colour index analysis. Three biological replicates were used for each experiment.

2.6. Biochemical Index

2.6.1. Preparation of Strawberry Homogenate

Strawberries were chopped into pieces and added to 1:1 ultrapure water. This mixture was homogenised in a homogenisation bag through beating.

2.6.2. Total Soluble Solids (TSS)

An ABBE refractometer (way-2W, INESA, Shanghai, China) was used to measure the TSS. The measured values were corrected according to the temperature coefficient of the refractive index, and measurements were recorded daily during storage [29].

2.6.3. Titratable Acid (TA)

The acid-base titration method with phenolphthalein was used as an indicator of TA. Tissue TA content was calculated according to the NaOH titrant consumption and expressed as a mass fraction (%) according to the following formula:

$$Titratable\ acid = \frac{V \times c \times (V_1 - V_0) \times f}{V_s \times m} \times 100\%$$

where V is the total volume of sample extract in mL; V_s is the volume of filtrate taken during titration in mL; c is the concentration of NaOH titrant in mol/L; V_1 is the volume of NaOH solution consumed for titration of filtrate in mL; V_0 is the volume of NaOH solution consumed for titration of distilled water in mL; m is the mass of sample in g; f is the conversion factor in g/mmol; Citric acid 0.064 was chosen as the f for this experiment.

2.6.4. SOD Activity

The strawberry homogenate was added to 8 times the volume of phosphate buffer (phosphate buffer: 0.1 mol/L pH 7–7.4). The mixture was centrifuged at 6000 rpm at 4 °C and the supernatant extracted. *SOD activity* was detected using an *SOD* assay kit (Nanjing Jiancheng Institute of Biological Engineering, Nanjing, China) at 450 nm using a UV spectrophotometer (UV-2600, Shimadzu, Kyoto, Japan). The *SOD inhibition* rate was obtained to calculate *SOD activity* (U) using the following formula:

$$SOD\ activity = \frac{SOD\ Inhibition \times 12}{50\%} \times P \div \frac{M}{V}$$

where P is the dilution; M is the strawberry weight in g; V is the volume of the added PBS in mL.

2.6.5. MDA

The extraction and reaction were performed using a plant *MDA* test kit (Nanjing Jiancheng Institute of Biological Engineering, Nanjing, China), and the results were detected using a UV spectrophotometer at 532 nm. *MDA content* (nmol/g) was calculated using the following formula:

$$MDA\ content = \frac{A_E - A_z}{A_S - A_Z} \times C \div \frac{M}{V}$$

where C is the concentration of the standard (10 nmol/mL); M is the weight of the plant tissue (g); V is the total amount of added extract (mL); A_E is the absorbance of the sample; A_S is the absorbance of the standard; A_z is the absorbance of the blank.

2.6.6. Vitamin C (Vc)

A standard curve for Vc was established using spectrophotometry, and measurements were recorded daily during storage. Each treatment was repeated three times.

2.6.7. CAT

The decomposition of H_2O_2 by CAT can be rapidly aborted by adding ammonium molybdate. The remaining H_2O_2 interacted with ammonium molybdate to produce a yellowish complex, which was measured at 405 nm, and CAT activity was calculated. CAT viability was assessed using a CAT assay kit (Nanjing Jiancheng Institute of Biological Engineering, Nanjing, China) (visible light).

2.7. Sensory Evaluation

The nine-point preference scale method for the organoleptic evaluation of strawberries is universally applicable for evaluating product acceptability and preference and is widely used in many fields for a wide range of products, such as food and beverages, cosmetics, and household products. Strawberries stored for seven days were evaluated for shape, colour, appearance, scent, and overall acceptability based on a nine-point preference scale [30,31] from 1 (dislike very much) to 9 (like very much). The hedonic evaluation scale was as follows: 1, dislike very much; 2, dislike a lot; 3, dislike moderately; 4, dislike slightly; 5, indifferent; 6, like slightly; 7, like moderately; 8, like a lot; and 9, like very much. Ten practitioners (five males and five females, aged 19–45 years) in food and pharmaceutical science and technology-related disciplines served as evaluators. The evaluators were trained for the sensory evaluation related to strawberries before the experiment. Sensory evaluation of the strawberries was performed on a separate test bench in a separate sensory laboratory. The assessors evaluated the appearance, colour, odour, shape, and overall acceptability of the strawberries at room temperature (approximately 25 °C). This method was used to determine the acceptability of SLN-CA-treated strawberries after seven days of storage and to verify the effect of SLN-CA on the sensory properties of the fruits.

3. Results and Discussion

3.1. Decay Index of Strawberry Spoilage

Decay of fruits and vegetables is one of the most important indicators for evaluating preservatives [28]. Regarding decay incidence (Figure 1a), treatment with 16.6 μL/mL of CA resulted in complete berry rotting on the third day, whereas treatment with 1.04 μL/mL of CA led to complete rotting on the fifth day. However, the treatment of strawberries with 1.05, 2.05, and 4.16 μL/mL SLN-CA positively reduced the rate of fruit rot compared to the that in the control. Even after treating strawberries with unencapsulated CA, the low-concentration treatment group showed much more severe decay than the blank control group. Strawberries treated with high concentrations of CA and SLN-CA did not exhibit mould, and their decay was due to ulceration of the strawberry peel caused by corrosion because of the high concentrations of CA [32,33]. Regarding the severity (Figure 1b), the same result of decay rate was observed. Pure CA treatment caused a large area of strawberry rot. In contrast, 2.05 and 4.16 μL/mL SLN-CA treatment could effectively alleviate the strawberry rot problem.

Strawberries treated with 8.3–1.04 μL/mL SLN-CA showed a reduction in decay incidence and severity relative to the blank control group. Among them, 1.05 μL/mL freshness solution-treated strawberries showed decay on the surface during the experiment, and the multiplication of the decay mainly caused their decay. The same effective concentration of SLN-CA freshness solution can release CA slowly so that strawberries are not initially exposed to a high concentration of essential oil. Therefore, strawberries treated with low concentrations of preservation solutions have insufficient effective concentrations to inhibit decay growth later. In contrast, strawberries treated with high concentrations of unencapsulated essential oil experienced severe rot due to the sudden release and high concentrations.

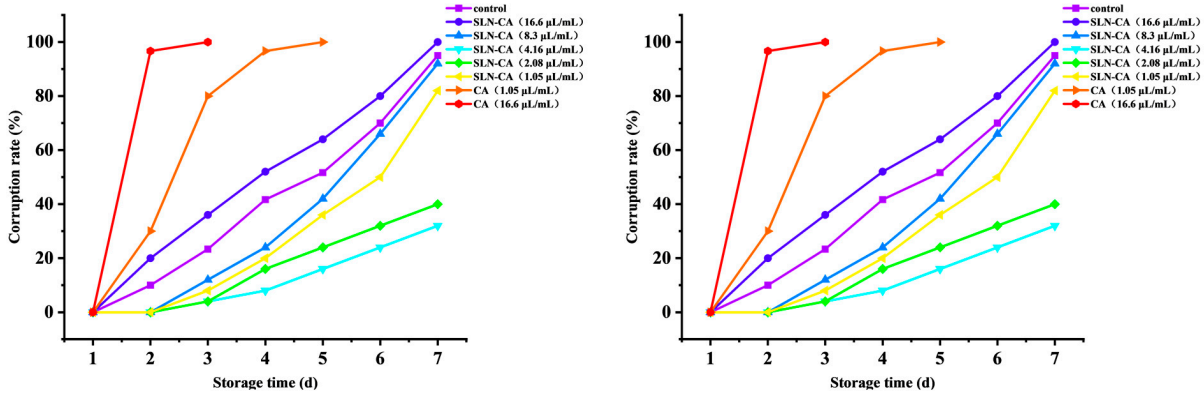


Figure 1. Effects of different treatments on incidence (**a**) and severity (**b**) of the postharvest decay in fresh strawberries during a seven-day storage period at 25 °C and 60% humidity.

3.2. Weight Loss

The change in weight during storage is an important indicator of strawberry quality. Weight loss during storage results from respiration and water loss due to transpiration [34]. The results showed that strawberries treated with a high concentration (16.6 μL/mL) of pure CA started to lose weight severely on the second day, and the weight loss rate was as high as 42.21 ± 10.39% on the third day. On the third day, the whole fruit was rotten; therefore, no further data were recorded for this group. In addition, strawberries treated with a low concentration (1.05 μL/mL) of pure CA showed a weight loss of up to 42.88 ± 5.81% and whole fruit decay on the fifth day (Table 1). The weight loss rate of strawberries treated with SLN-CA was lower than that of strawberries treated with pure CA, and no serious rotting occurred within seven days. Moreover, treatment with 8.3–2.08 μL/mL SLN-CA did not cause significant weight loss in strawberry fruits compared to the control group ($p \geq 0.05$). The overall weight loss of the 8.3–2.08 μL/mL SLN-CA treatments was near 21.44%. The highest concentration (16.6 μL/mL) of preservation solution resulted in a slightly higher weight loss compared to the other concentration groups. The weight loss rate was maintained at 28.98 ± 3.11% on the seventh day. Strawberries treated with a 1.05 μL/mL preservation solution had a better preservation effect than other concentration groups ($p < 0.05$), and the weight loss rate was maintained at 16.72 ± 1.33% at the seventh day (Figure 2). SLN-CA can form a stable complex system that forms a protective film on the surface of strawberries, reducing evaporation and oxidation, preventing microbial contamination, and thus reducing the weight loss and decay incidence of strawberries. However, unencapsulated CA can burn fruit cells [31]. This conclusion was also reflected in a study on the application of thyme essential oil for the preservation of freshly cut apples [33]. The photographs of strawberries in Figure 3 show that SLN-CA treatment is effective in alleviating rotting in strawberries compared to the control group.

3.3. Firmness

Fruit firmness is an important indicator of shelf life and an important aspect for evaluating quality and commodity value [35]. The initial firmness of the strawberries in the experiment was 115 ± 7.62 gf. The firmness test results for each test group, as shown in Figure 3, revealed that the strawberries treated with 2.08 μL/mL SLN-CA had the best peel firmness, with 117 gf (Figure 4a). There were no significant differences ($p > 0.05$) in the flesh firmness of strawberries treated with 4.16, 2.08, and 1.05 μL/mL SLN-CA for seven days with 72 gf compared to that in the blank control group. The good firmness is due to the SLN-CA treatment, which reduces the likelihood of strawberries being infected with pathogenic fungi such as *Rhizopus* spp. and *Botrytis cinerea* and reduces the enzymatic digestion of strawberry cells by microorganisms. Strawberries contain a large amount

of water, and decay can grow on the surface and inside the fruit, consuming nutrients and water. This can cause strawberries to become soft and sticky, eventually losing their crispness and flavour. Additionally, decay can secrete acids and enzymes, which can accelerate the decay and spoilage of strawberries. Therefore, decay on strawberries can lead to a decrease in firmness. These enzymatic reactions cause the softening of strawberries [36]. Notably, after seven days of storage, the firmness of the pure CA treatment group was lower compared to that of the blank control group (Figure 4b) because excessive essential oil treatment poisoned the strawberries, causing cell destruction and accelerating the aging of the strawberry tissue, resulting in a decrease in firmness [18].

Table 1. Results of the effect of different treatments on the weight of strawberries before and after storage and weight loss rate. Different letters above the columns indicate significant differences among the treatments based on Duncan's multiple-range test ($p < 0.05$); D means the strawberry is completely rotten and nothing is measured.

Processing Means	Weight before (g)	Weight afterwards (g)	Weight Loss Rate (%)
CA (1.05 μL/mL)	12.14 ± 2.05 ^{a}	D	D
CA (16.6 μL/mL)	12.92 ± 1.83 ^{a}	D	D
SLN-CA (1.05 μL/mL)	12.38 ± 2.23 ^{a}	10.317 ± 2.2 ^{b}	16.72 ± 1.33 ^{a}
SLN-CA (2.08 μL/mL)	12.45 ± 2.19 ^{a}	9.83 ± 2.14 ^{b}	21.04 ± 2.22 ^{b}
SLN-CA (4.16 μL/mL)	12.63 ± 2.62 ^{a}	10.01 ± 2.49 ^{b}	20.72 ± 4.95 ^{b}
SLN-CA (8.32 μL/mL)	12.76 ± 1.95 ^{a}	9.93 ± 1.88 ^{b}	22.17 ± 3.36 ^{b}
SLN-CA (16.6 μL/mL)	12.29 ± 1.18 ^{a}	8.57 ± 1.12 ^{a}	28.98 ± 3.11 ^{c}
Control	12.18 ± 1.65 ^{a}	9.51 ± 1.584 ^{b}	21.98 ± 4.33 ^{b}

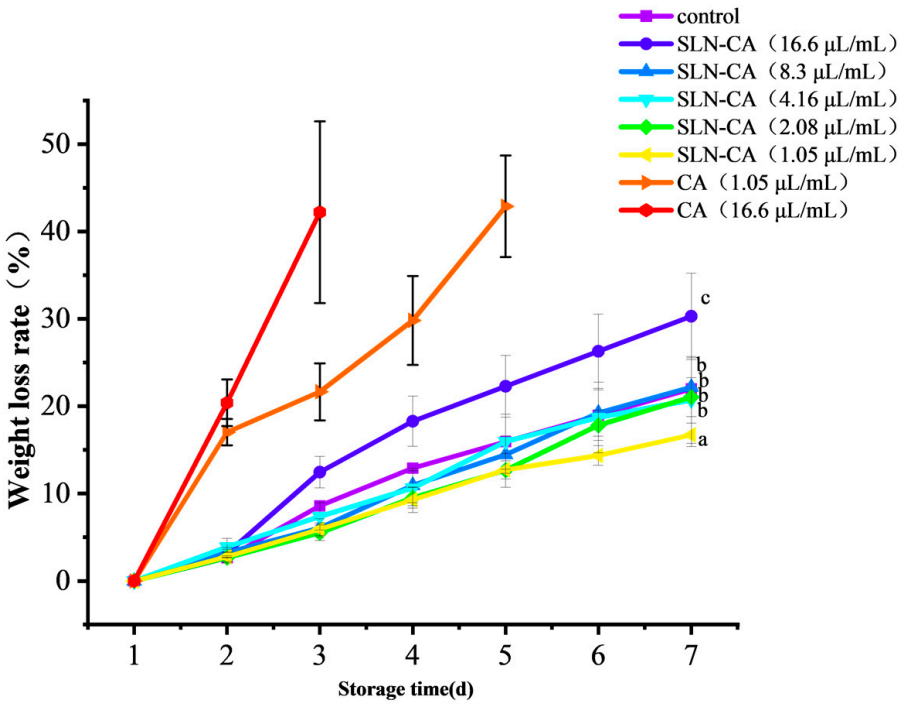
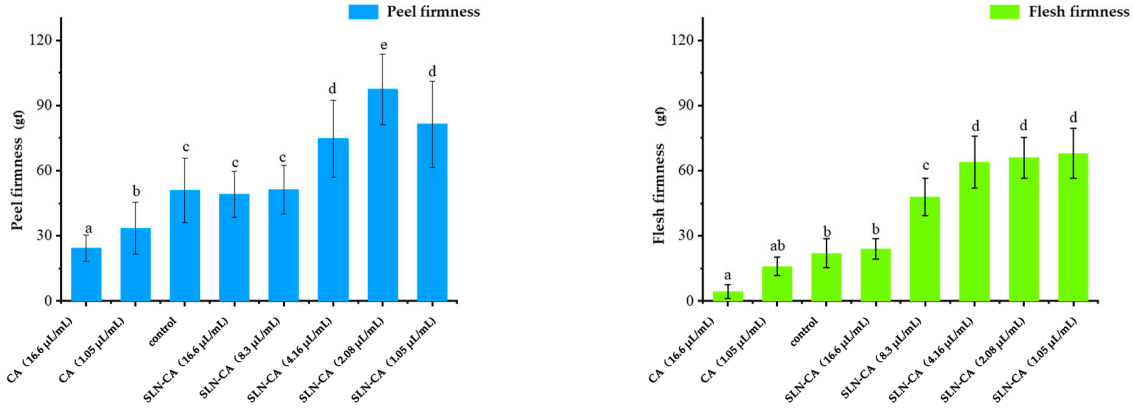


Figure 2. The change curves of the weight loss rate of strawberries treated with different concentrations of SLN-CA preservation solution and CA for seven days. Error bars show the standard deviation of the means (thirty strawberry repeats); different letters above the columns indicate significant differences among the treatments based on Duncan's multiple-range test ($p < 0.05$).

Figure 3. Pictures of strawberries stored at 25 °C and 60% humidity for seven days after different treatments.



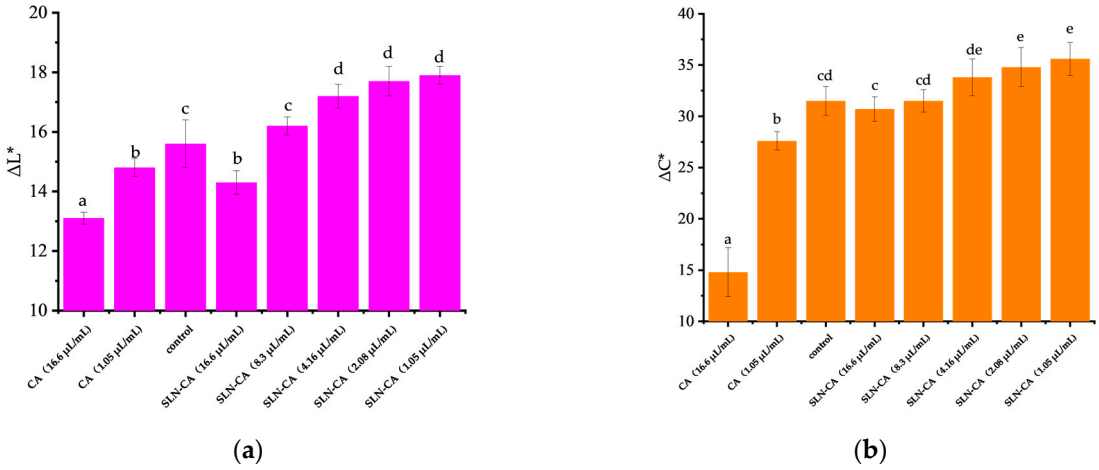
(**a**) (**b**)

Figure 4. Strawberry peel firmness (**a**) and strawberry flesh firmness (**b**) in different treatments and blank control during seven days. Different letters above the columns indicate significant differences among the treatments based on Duncan's multiple-range test ($p < 0.05$).

3.4. Colour Variation and Visual Appearance

Colour and appearance are important indicators of consumer perceptions of fruit and vegetable quality. The colour changes in fresh-cut apples in the different treatment groups are shown in Figure 4. ΔL* and ΔC* were chosen as the colour indices. The ΔL* value indicates the brightness of the sample, which is one of the indicative parameters of surface darkening due to enzymatic browning or pigment aggregation during storage; the lower the value, the more serious the browning. The ΔC* value indicates the colour saturation of the sample; the higher the value, the brighter the quality. After seven days of storage, the treated strawberries were brighter than the blank controls ($p < 0.05$). However, the 16.6 μL/mL SLN-CA- and pure CA-treated groups were less bright compared to the blank control (Figure 5a) because the excessive essential oil burned the strawberry skin and poisoned the strawberries, causing a severe decrease in brightness [18,31,37]. The ΔC* value indicated the colour saturation of the samples. The colour saturation results after seven days of storage were similar to the brightness results. Strawberries treated with 2.08 and 1.05 μL/mL SLN-CA had higher ΔC* compared to that of the blank control and other treatments ($p < 0.05$). Treatment with pure CA significantly reduced ΔC* in strawberries (Figure 5b). High concentrations of CA significantly increased the degree

of browning in strawberries, probably because the high concentration of CA disrupts the strawberry cells, causing a loss of separation between enzymes and substrates regionally distributed in the strawberry tissue and accelerating enzymatic browning. High concentrations of CA are toxic to fruits and vegetables and have been reported in various fruits and vegetables. Adding rosemary, thyme, and oregano CA to lettuce, coleslaw, and chopped cabbage reduced the product appearance scores to unacceptable levels throughout storage, and all the products lost their commercial value after 8 days of storage [38]. In addition, the slow release of cinnamaldehyde contained in the SLN-CA played a role in avoiding the toxicity of high concentrations of CA in strawberry cells. Therefore, the brightness and saturation of the SLN-CA treatment group were significantly higher than those of the CA group at the same essential oil concentrations.



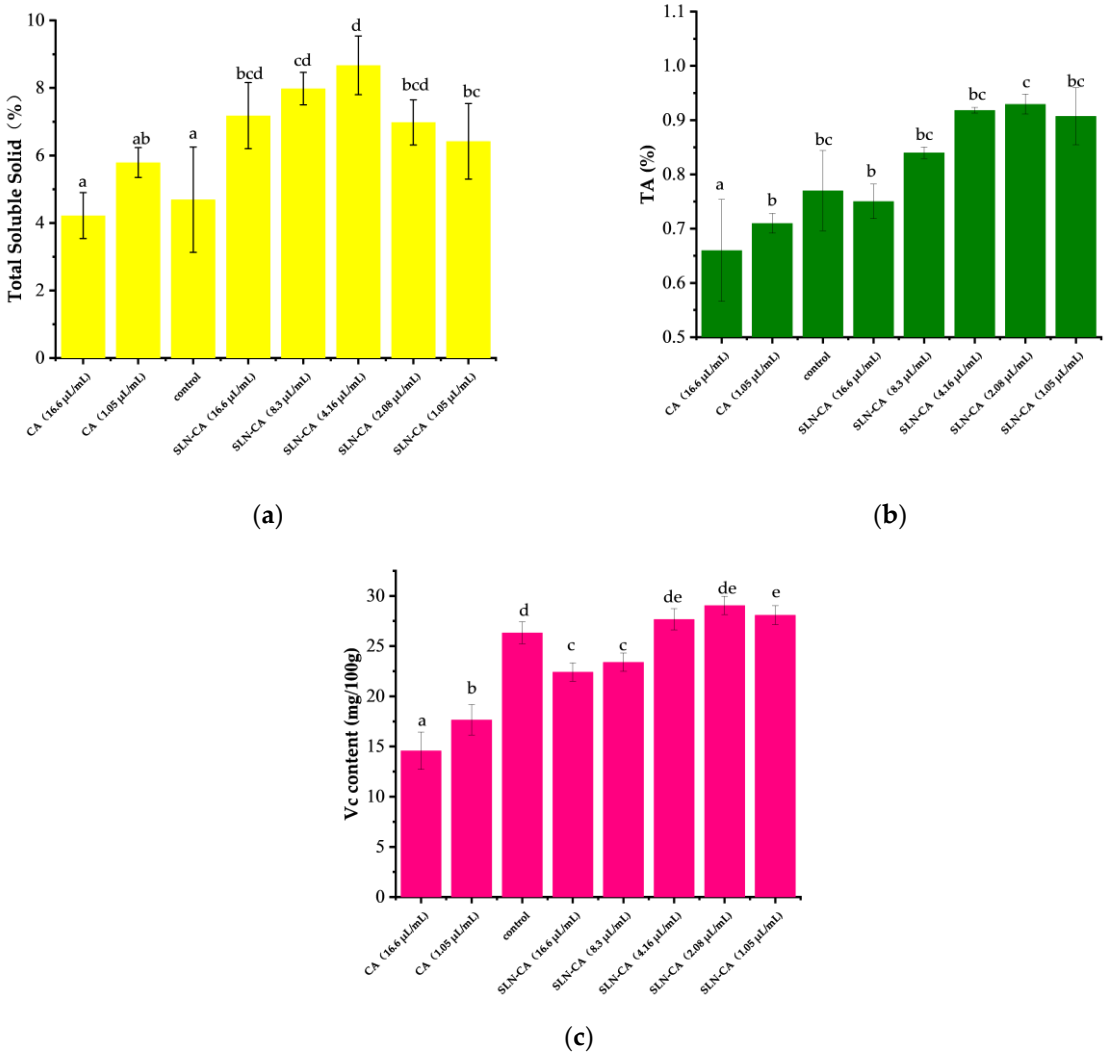
(**a**) (**b**)

Figure 5. Strawberry lightness (**a**) and strawberry colour saturation (**b**) in different treatments and blank control during seven days. Different letters above the columns indicate significant differences among the treatments based on Duncan's multiple-range test ($p < 0.05$).

3.5. Vc, TSS, and TA

TSS, including sugars, acids, vitamins, and minerals, has a crucial influence on strawberry quality. The decomposition of TSS and the accumulation of acids by microbial metabolism are the reasons for the rapid decline in the quality of strawberries in the middle and late stages of postharvest storage. The TSS of strawberries treated with SLN-CA was higher compared to that of the blank treatment group (Figure 6a) ($p < 0.05$), possibly because of two factors. First, after treatment with SLN-CA, some microorganisms on the surface of the strawberries were inhibited, protecting the integrity of the cells and allowing the enzymes and substrates distributed regionally in the strawberry tissues to remain separate and not digested enzymatically. Second, the lipid nanoparticles were coated on the surface of the strawberry, forming a solid lipid-cling film, creating an aerated environment with low oxygen and high carbon dioxide and reducing the metabolic rate in strawberry cells. In the CA-treated group, the essential oil was not encapsulated and acted at a high initial release concentration, scorching the cells and decreasing the TSS. Organic acids are essential components of strawberry flavour. Changes in acidity are mainly influenced by the metabolic rate, particularly the respiration rate. Respiration depletes organic acids; therefore, the acidity decreases during storage, which is the leading cause of fruit ageing [39]. The Vc contents of the different treatment groups after seven days of storage are shown in Figure 6b. The decrease in TA content in the 1.05 μL/mL SLN-CA-treated group may be due to two factors: First, the concentration was too low to inhibit microbial growth, resulting in acid accumulation via microbial metabolism. Second, microbial multiplication disrupts the integrity of strawberry cells, causing a loss of separation between enzymes and substrates regionally distributed in the tissue and accelerating the breakdown of TA. In contrast, the higher TA content in the pure CA-treated group may be due to the high

concentration of CA that disrupts the integrity of strawberry cells [38]. The Vc content of the different treatment groups after seven days of storage is shown in Figure 6c, and the results were similar to those of TSS and TA.



(**a**) (**b**)

(**c**)

Figure 6. Result of Total soluble solids (**a**), *Titratable acid* (**b**), and Vitamin C content (**c**) in different treatments and blank control during seven days. Different letters above the columns indicate significant differences among the treatments based on Duncan's multiple-range test ($p < 0.05$).

3.6. SOD, MDA, and CAT

The effects of the different treatments on the *SOD*, *MDA*, and Vc of strawberries after seven days of storage are shown in Table 2.

Antioxidant enzymes play important roles in the suppression of oxidative stress. Strawberries constantly produce substances that are harmful to cells, such as H_2O_2. To reduce cell damage, strawberries must produce more antioxidant enzymes to remove harmful substances. Free-radical-induced oxidative stress plays an important role in fruit senescence.

SOD is the main reactive oxygen species scavenging enzyme, which catalyses the conversion of O^{2-} to H_2O_2 and O_2, keeping free radicals at a low level and avoiding membrane damage. The first line of defence for scavenging reactive oxygen species in plant cells is important for maintaining plant cell activity [40]. Strawberries treated with 1.05 μL/mL of SLN-CA for seven days had the highest *SOD* activity, reaching 214.77 ± 0.65 U/g, which was higher compared to that of the blank control ($p < 0.05$) and 1.05 μL/mL CA-treated group. CA-treated strawberries with 16.6 μL/mL had 197.86 ± 1.83 U/g after seven days

of storage, which was lower compared to that of the blank control ($p < 0.05$). Similarly, CAT activity in SLN-CA-treated strawberries was significantly higher compared to that in the immediate treatment groups with unencapsulated CA. Strawberries treated with 2.08 µL/mL SLN-CA showed higher CAT activity compared to that with the other groups ($p < 0.05$).

Table 2. Results of the effect of different treatments on *SOD*, *MDA*, and Vc of strawberries before and after storage and weight loss rate. Different letters above the columns indicate significant differences among the treatments based on Duncan's multiple-range test ($p < 0.05$).

Processing Means	*SOD* (U/g)	CAT (U/g)	*MDA* (nmol/g)
CA (1.05 µL/mL)	207.25 ± 1.62 ^{a}	88.21 ± 7.62 ^{bc}	577.75 ± 20.68 ^{de}
CA (16.6 µL/mL)	197.86 ± 1.83 ^{b}	64.98± 8.69 ^{a}	598.63 ± 17.56 ^{e}
SLN-CA (1.05 µL/mL)	214.77 ± 0.65 ^{e}	92.91 ± 5.11 ^{bc}	546.83 ± 11.43 ^{c}
SLN-CA (2.08 µL/mL)	212.28 ± 1.08 ^{cd}	98.6 ± 6.87 ^{b}	463.07 ± 6.92 ^{a}
SLN-CA (4.16 µL/mL)	213.02 ± 1.34 ^{de}	94.6 ± 6.42 ^{bc}	523.23 ± 6.51 ^{b}
SLN-CA (8.32 µL/mL)	210.87 ± 0.86 ^{c}	88.45 ± 3.08 ^{bc}	565.93 ± 8.66 ^{cd}
SLN-CA (16.6 µL/mL)	202.08 ± 1.06 ^{b}	82.65 ± 7.16 ^{b}	580.69 ± 8.93 ^{de}
Control	210.42 ± 0.39 ^{c}	94.56 ± 5.44 ^{bc}	558.48 ± 7.65 ^{cd}

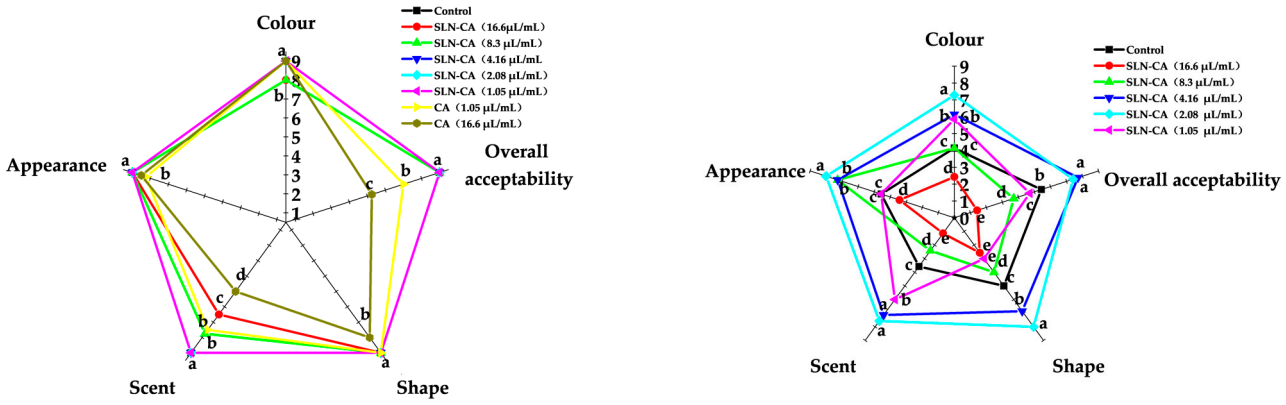
MDA is the final product of membrane lipid peroxidation, and SLN-CA treatment reduced the *MDA* content in strawberry cells, demonstrating that SLN-CA treatment could effectively reduce the peroxidation of strawberry cell membranes and further supporting that SLN-CA treatment can effectively maintain the integrity of cells and tissues and the fresh quality of strawberry fruit. The *MDA* concentration in strawberries treated with SLN-CA was significantly lower compared to that in strawberries naturally treated with unencapsulated CA. The lowest *MDA* concentration was observed in 2.08 µL/mL SLN-CA-treated strawberries ($p < 0.05$).

The effect of the different CA treatments on *SOD*, CAT, and *MDA* in strawberries could be due to the effective reduction in the growth of microorganisms. The microorganisms on the surface of the strawberry draw nutrients from the strawberry cells and destroy them, leading to their decay. However, unencapsulated CA treatment at high concentrations burned strawberry cells, destroying their cellular integrity.

3.7. Sensory Evaluation

The pungent smell and taste of essential oils can affect the organoleptic properties of food [41]. So, an organoleptic evaluation was carried out on strawberry fruit on the first and seventh days of storage at 25 °C. Strawberry fruit colour, scent, appearance, shape, and overall acceptability were rated on a nine-point preference scale ranging from 1 (highly disliked) to 9 (extremely liked). On day one (Figure 7a), shape, colour, appearance, scent, and overall acceptability in the 4.16, 2.08, and 1.05 µL/mL SLN-CA-treated groups did not significantly differ compared to the blank control group ($p > 0.05$). Unwrapped CA has a pungent odour that affects the sensory odour of strawberries. The 16.6 µL/mL CA-treated group had an odour score of only four and an overall acceptability score of five. In comparison, the 1.05 µL/mL CA-treated group had an odour score of only seven and an overall acceptability score of seven, indicating that the unencapsulated CA greatly affected the sensory odour quality of the strawberries. After seven days (Figure 7b), the results were recorded as 0 and not plotted in the graph because the 16.6 and 1.05 µL/mL CA-treated groups were severely decayed at four and six days of storage, respectively. Therefore, the significance of the sensory evaluation was lost. The highest sensory evaluation score between 7 and 8 and between 6 and 7 was overserved for 2.08 and 4.16 µL/mL SLN-CA-treated groups, respectively. These groups also performed better than the blank control group. However, the SLN-CA treatment of more than 8.3 µL/mL negatively affected the sensory odour of strawberries, and the score dropped between 1 and 4. These results are

consistent with those of other studies, indicating that high concentrations of essential oils have a negative impact on the overall acceptability of food. For example, when evaluating the sensory characteristics of freshly cut sweet melons with lemongrass, the addition of 0.7% lemongrass to the coating formulation significantly reduced the sensory score [42].



(**a**) (**b**)

Figure 7. Sensory characteristics of strawberries on the first (**a**) and seventh day (**b**) of storage at 25 °C. In the control group of first (**a**), the SLN-CA score for a concentration range of 1.05–4.16 μL/mL was 9. The nine-point hedonic evaluation scale was used as follows: 9, like very much to 1, dislike very much. For each sample, the means designated by different letters are significantly different ($p < 0.05$).

4. Conclusions

One of the most critical indicators for evaluating preservatives is their ability to prevent mould and decay of fruits and vegetables. The positive effect of SLN-CA on freshness was also confirmed by tests on fresh strawberries, in which SLN-CA treatment significantly reduced the incidence and severity of spoilage. As a potential preservative, SLN-CA can also reduce the *MDA* content of cells, increase *SOD* and CAT activity, and prevent cell damage. SLN-CA, compared to CA, avoids the toxic effects of high CA concentrations on strawberry cells, maintains better colour and appearance, and reduces the adverse sensory effects of CA on strawberries. Conclusively, this study tested the potential application of SLN-CA in the preservation of strawberries to provide efficient, long-lasting, natural, and pollution-free preservatives for future agricultural and horticultural industries.

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