Coating of Tomatoes (Solanum lycopersicum L.) Employing Nanoemulsions Containing the Bioactive Compounds of Cactus Acid Fruits: Quality and Shelf Life

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Abstract: This study was aimed at evaluating the effect of a nanoemulsion containing the bioactive compounds of Opuntia oligacantha (C.F. Först) on maintaining and improving the quality of the shelf life of tomato fruits. The nanoemulsion was applied as a coating on the whole fruits during physiological maturity; the treatments were thus: Control 1 without coating (C1); Control 2 with food-grade mineral oil coating (C2); and nanoemulsions that were diluted with mineral oil at 2.5% (DN2.5), 5% (DN5), 10% (DN10), and 20% (DN20). Further, the following parameters were determined for 21 days: the percentage weight loss, firmness, colour, pH, titratable acidity, total soluble solids, ascorbic acid content, total phenols, flavonoids, tannins, antioxidant activities DPPH and ABTS, and the histological evaluation of the pericarp of the fruits. Significant differences (\(p < 0.05\)) were observed during the treatments; DN10 and DN20 obtained the best weight loss results (3.27 ± 0.31% and 3.71 ± 0.30%, respectively) compared with C1 and C2. The DN5 and DN20 textures exhibited the highest firmness (11.56 ± 0.33 and 11.89 ± 1.04 N, respectively). The antioxidant activity (DPPH on Day 21) was higher in the DN20 treatment (48.19 ± 0.95%) compared with in C1 (39.52 ± 0.30%) and C2 (38.14 ± 0.76%). Histological evaluation revealed that the nanoemulsion coating allowed a slower maturation of the cells in the pericarp of the fruits. The nanoemulsion, as a coat, improved the quality and valuable life of the tomato regarding its physiological changes during transport and storage [3]. To mitigate these setbacks, preservation methods, such as the utilization of controlled atmospheres, refrigeration, chemical treatments, and coatings, have been developed in recent years [4]. Edible coatings are thin layers which act as a barrier between food and its environment [5]. Edible coatings are

1. Introduction

The tomato (Solanum lycopersicum L.) is among the most valuable crops worldwide owing to its versatile preparation and consumption, as well as abundant vitamins, such as Vitamins C and E, and minerals, carotenoids, and polyphenols [1,2]. Unfortunately, the fruit exhibits a reduced post-harvest life. As a climacteric fruit, tomato undergoes considerable physiological changes during transport and storage [3]. To mitigate these setbacks, preservation methods, such as the utilization of controlled atmospheres, refrigeration, chemical treatments, and coatings, have been developed in recent years [4]. Edible coatings are
attracting attention because of their inexpensiveness and composition of environmentally benign materials [6–8].

Presently, the bioactive compounds of plants and fruits are being extracted and employed for coatings because they prevent the deterioration of food [9]. Xoconostle (*Opuntia oligacantha* CF Först) is a fruit from Central Mexico, which contains phenols, flavonoids, and betalains [10]. Further, xoconostle, exhibiting antioxidant [11] and antibacterial [12] activities, can be ideally incorporated into food matrices. Another valuable source of bioactive compounds, which is unique because of its biological activity, is orange essential oil (*Citrus sinensis*). Hashthjin and Abbasi [13] reported that orange contains a high percentage of limonene, which accounts for its consideration as a natural antimicrobial [14]. However, since these bioactive compounds are labile, it is necessary to encapsulate them in stable matrices to ensure their subsequent utilization and effect [15].

Nanoemulsions, which are a novel platform for encapsulating bioactive compounds, have attracted attention because they do not influence the organoleptic properties of the foods in which they are incorporated. A nanoemulsion is an emulsion with a drop size of \( r < 100 \text{ nm} \), which ensures a good semi-permeable barrier against \( \text{CO}_2 \) and \( \text{O}_2 \) [16]. These systems are kinetically stable without apparent flocculation or coalescence [17] and offer certain advantages, such as small droplet size, optical clarity, high surface–volume ratio, excellent long-term stability, and high availability of the encapsulated compounds, over conventional emulsions. Owing to these characteristics, nanoemulsions can be employed as releasing systems for the bioactive compounds [18] in different foods, including apples [19], grapes [20], and strawberries [21]. The objective of this study was to evaluate the effect of the nanoemulsion of xoconostle extract as a novel coating strategy in the conservation at the cellular level and the postharvest quality during its useful life of tomato fruits. In addition, the effect on the physicochemical parameters, firmness, bioactive compounds, and antioxidant activity was evaluated.

2. Materials and Methods

2.1. Materials

The saladette-type tomato fruits of the Reserva F1 variety were obtained from greenhouses in Santiago Tulantepec de Lugo Guerrero, Hidalgo, Mexico (20°02’23” N, 98°21’27” W) during physiological maturity. Regarding the preparation of the nanoemulsion, the Ulapa variety of xoconostle fruit (*Opuntia oligacantha* C. F. Först.), which was obtained from the Tetepango municipality of Hidalgo, Mexico (20°06’11” N, 99°09’23” W), was utilized. The orange essential oil (Meyer, Mexico City, Mexico) and soy lecithin (Reasol, Mexico City, Mexico) were also utilized.

The following reagents were utilized for the analyses: food-grade mineral oil was obtained from UltraSource (Kansas City, MO, USA). Potassium persulfate, Folin–Ciocalteu reagent, ascorbic acid, quercetin, 2,2-diphenyl-1-picrylhydrazil (DPPH), 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), paraffin, and 2-methoxyethanol were obtained from Sigma-Aldrich (St. Louis, MO, USA). Methanol, ethanol, sodium bicarbonate, sodium carbonate, sodium hydroxide, hydrochloric acid, metaphosphoric acid, and glacial acetic acid were obtained from J.T. Baker (Fisher Scientific SAS, Lenexa, KS, USA). Gallic acid and aluminum trichloride were obtained from Fermont (Monterrey, Mexico). Potassium ferrocyanide and sodium salt, as well as 2,6-dichlorophenol indophenol, were obtained from Honeywell (Morristown, NJ, USA). Formaldehyde, xylene, and methyl salicylate were of analytical grade.

2.2. Development of Nanoemulsion

The nanoemulsion (W/O) was prepared according to the method of Cenobio-Galindo et al. [22]. Briefly, 70% of the orange essential oil was added as the continuous phase, and soy lecithin was employed as a surfactant in 20% and 10% aqueous extracts of xoconostle (the dispersed phase). The mixture was sonicated (Sonics Vibra-Cell, Newtown, CT, USA) for 30 min with a 6 mm probe at an amplitude of 80% and a frequency of 20 kHz.
Subsequently, the drop-size distribution was determined via the dynamic laser-light-scattering technique at an angle of 90°; the zeta potential (ζ) was measured by a Zetasizer Nano-ZS2000 analyzer (Malvern Instruments, Worcestershire, UK). The nanoemulsion was stored in a closed, dark container at 6 °C before it was utilized.

2.3. Nanoemulsion Fruit Coating

The tomato fruits, which were at physiological maturity, were washed and disinfected with a sodium hypochlorite solution (150 ppm) for 5 min, after which they were dried at 20 °C. Afterwards, they were completely covered by sprinkling according to the following treatments: without coating (C1); with food-grade mineral-oil coating only (C2); and with the nanoemulsion that was diluted to 2.5% (DN2.5), 5% (DN5), 10% (DN10), and 20% (DN20) in the food-grade mineral oil, affording a total of six treatments. The differently treated samples were stored in a refrigeration chamber at 6 °C and evaluated every seven days for 21 days.

2.4. Evaluation of Physicochemical Parameters

Regarding the weight loss percent, a digital scale (WMF, Germany) was used, following the application of the corresponding coating. The tests were performed in triplicates on each test day [23].

The colour of the fruits were determined by a CR-400/410 colourimeter (Konica Minolta, Japan). Three measurements were conducted on five fruits from each treatment per evaluation day [2], thus obtaining the parameters of L* (lightness), a* (red to green), and b* (blue to yellow).

The pH of the previously filtered tomato juice was determined according to the official methods of the Association of Official Agricultural Chemists (AOAC) edited by Horwitz [24] (Official Method 981.12) by a 211 microprocessor (Hanna, RI, USA). To determine the titratable acidity (Official Method 942.15), 10 and 50 mL of the juice and distilled water, respectively, were titrated against sodium hydroxide (0.1 N); the results were expressed as a percentage of the citric acid. The total soluble solids were analyzed according to Official Method 932.12 and the juice was filtered and determined by a refractometer (Pocket PAL-3; Atago, Columbia, DC, USA); the results were expressed in °Brix.

To determine the texture, the method, which was described by Guerreiro et al. [25], was employed through a compression test employing a texture analyzer (CT3; Brookfield, Harlow, UK) that was fitted with a 6 mm-diameter conical tip probe at a speed of 1 mm/s and a distance of 5 mm. The results were expressed in Newtons (N).

2.5. Bioactive Compounds and Antioxidant Activity of Tomato

2.5.1. Ascorbic Acid Content

The Official Method 967.21 [24] was employed to determine the ascorbic acid content via the 2,6-dichlorophenol indophenol visual titration method. To analyze the samples, 10 and 100 mL of the juice and 3% metaphosphoric acid, respectively, were obtained. This mixture filtered and titrated with a dye solution until the persistent pink colour turned for at least 15 s. The results were expressed as mg/100 mL.

2.5.2. Extraction of Bioactive Compounds

The bioactive compounds in the tomato were extracted, following the method of Sharmin et al. [26] with a few modifications. Briefly, an ethanol/water solution (50/50) was macerated for 2 h in complete darkness and centrifuged in a Z 36 HK centrifuge (Hermle, Germany) for 5 min at 4 °C and 12,000 rpm. Afterwards, the extracts were stored in dark containers at 6 °C until they were utilized.

2.5.3. Total Phenol Content

The total phenol content was quantified via the Folin–Ciocalteu method, following the method that was described by Singleton et al. [27]. Briefly, 0.5 mL of the previously
obtained extract was mixed with 2.5 mL of the Folin–Ciocalteu reagent that was diluted with distilled water in a 1:10 (v/v) ratio. After 8 min, 2 mL of sodium carbonate (7.5%) was added, and the mixture was allowed to stand for 2 h in total darkness, after which the absorbance was analyzed by a spectrophotometer at 760 nm. A gallic acid standard curve was constructed to express the results, which were expressed in mg gallic acid equivalents (GAE)/100 g of fruit. The tests were performed in triplicates.

2.5.4. Total Flavonoid Content

The flavonoid content was estimated, following the method described by Arvouet-Grand et al. [28] with some modifications. Briefly, a methanolic solution of aluminum trichloride was prepared at 2% (w/v), 2 mL of this solution was added to 2 mL of the extract, and the mixture was allowed to react in the dark for 10 min, after which it was analyzed at an absorbance of 415 nm. Next, the total flavonoid content was determined by a quercetin standard curve. The analysis was performed in triplicate, and the results were expressed in mg quercetin equivalents (QE)/100 g of fruit.

2.5.5. Tannin Content

The tannin content was determined via the method of Price and Butler [29] with a few modifications. Briefly, 200 µL of the extract and 600 µL of iron trichloride, which were prepared in 0.1 N hydrochloric acid at 0.1 M, were mixed and allowed to react for 5 min in the dark. Subsequently, 600 µL of 8 mM potassium ferricyanide was added. After standing for 10 min, the samples were analyzed at 720 nm. The results were expressed in mg catechin equivalents (CE)/100 g of fruit, and the tests were performed in triplicates.

2.5.6. Inhibition of the DPPH Radical

The method of Brand-Williams et al. [30] was employed to determine the inhibition of the DPPH radical. Briefly, 0.0078 g of DPPH was added to 100 mL of 80% methanol. The mixture was allowed to stand in total darkness for 2 h with constant stirring, after which it was calibrated to an absorbance of 0.7 ± 0.01 nm. Subsequently, 2.5 mL of this DPPH mixture was added to 0.5 mL of the tomato-fruit extract (ethanol/water) and allowed to stand again for 1 h. The samples were analyzed by a spectrophotometer at 515 nm, and the results were expressed as a percentage of the inhibition.

2.5.7. Inhibition of the ABTS Radical

The method proposed by Re et al. [31] was employed for the inhibition assays of ABTS. Briefly, 7 mM of ABTS was mixed with 10 mL of distilled water and reacted with 2.45 mM potassium persulfate in a 1:1 ratio for 16 h with stirring in complete darkness. Afterwards, it was adjusted by 20% ethanol until an absorbance of 0.7 ± 0.01 nm was obtained. Thereafter, 2 mL of the mixture was added to 200 µL of the extract and allowed to react for 6 min in total darkness, after which the absorbance was analyzed at 734 nm. The tests were performed in triplicates, and the results were expressed as a percentage of the inhibition.

2.6. Histological Evaluation

Regarding the histological sections, a 1 cm² area was taken from the equatorial part (the pericarp and mesocarp) of the fruit. Next, following the method of Ramirez-Godina et al. [32] with a few modifications. Briefly, the tissue was fixed in formalin–aceto–alcohol (FAA), which is a mixture of 96% ethanol, distilled water, formaldehyde (37–40%), and glacial acetic acid in a 50:35:10:5 ratio. Afterwards, the tissue was dehydrated in a TP1020 automatic tissue processor (Wetzlar, Germany) for 1 h in each of the following solutions of distilled water: 60%, 70%, 80%, 90%, 96%, and 100% alcohol, followed by xylene for 3 h. Next, the tissue was processed in two different paraffin solutions for 1 and 2 h, respectively. The plant tissue was placed in hot paraffin blocks, cooled to room temperature, and cut transversely by a manual rotary microtome RM2125RT (Wetzlar, Germany). The
sections were mounted on slides, spread in a water bath at 37 °C, and dried in an oven for ~15 min at 70 °C. The fixed sections were stained with Safranin-O and Fast Green FCF to observe the lignification changes in the cell walls of the pericarp tissue of the tomato fruits (100X) via a light microscope, model CX31RBSF (Olympus, Tokio, Japan). The results were recorded by a video camera, Evolution VF (Media Cybernetics, Rockville, Maryland, USA), and the resulting images were digitally processed and saved in the format for analysis.

2.7. Statistical Analysis

A completely randomized design with three replicates was employed here. The analysis was performed by ANOVA, where significant differences (p < 0.05) were observed between the treatments. The means were compared via the Tukey method employing the NCSS 2007 software.

3. Results

3.1. Droplet Size and ζ Potential of the Nanoemulsion

The obtained W/O dispersion exhibited a droplet size of 91 ± 9 nm, as well as a ζ of −197 ± 4 mV, indicating the excellent stability of the system against phase separation (no flocculation or coalescence that could compromise the characteristics of the system was observed).

3.2. Physicochemical Characterization of the Coated Fruits

The nanoemulsion–coated fruits exhibited a low weight loss percent, which was evident from day 14, highlighting the DN10 and DN20 treatments. However, these differences became evident on day 21, indicating that C1 exhibited a final weight loss of >6% (Figure 1), which demonstrated the positive effect of the applied coatings.

Regarding the firmness (Figure 2) a gradual decrease was observed in all the treatments with respect to time, although C1 exhibited the greatest loss in firmness, which became very evident from day 7, and finished the analysis with 8.91 ± 0.69 N, while C2 finished the test with 9.48 ± 0.43 N compared with DN5 (11.56 ± 0.33 N) and DN20 (11.89 ± 1.04 N), which presented greater firmness.

![Figure 1. Percentage of weight loss in tomato fruits coated with nanoemulsion during storage at 6 °C.](image-url)
Figure 2. Firmness in tomato fruits coated with nanoemulsion during storage at 6 °C.

Table 1 presents the results regarding the external colour of the tomato fruits, obtaining significant differences \( (p < 0.05) \) in all the evaluated parameters. A decrease was observed in the \( L^* \) parameter with respect to the storage time for all treatments because the fruit became darker owing to the accumulation of carotenoids. Further, a significant decrease \( (p < 0.05) \) was observed in parameter \( a^* \) (green to red) for all the treatments after 21 days. The controls (C1 and C2) already exhibited positive values, which indicated the rapid maturation of the yellow) also decreased mainly in uncoated fruits (C1), indicating rapid maturation, as in the other colour parameters.

Table 1. External color of tomato fruits coated with nanoemulsion during storage.

| Days | C1         | C2         | DN2.5      | DN5        | DN10       | DN20       |
|------|------------|------------|------------|------------|------------|------------|
| 0    | 46.81 ± 0.40 \( \text{aA} \) | 46.22 ± 0.59 \( \text{aA} \) | 46.58 ± 0.50 \( \text{aA} \) | 46.44 ± 1.71 \( \text{aA} \) | 46.76 ± 1.17 \( \text{aA} \) | 45.95 ± 0.66 \( \text{aA} \) |
| 7    | 44.31 ± 1.46 \( \text{ab} \) | 44.93 ± 0.67 \( \text{aA} \) | 44.11 ± 1.38 \( \text{ab} \) | 43.46 ± 0.90 \( \text{ab} \) | 44.83 ± 1.02 \( \text{ab} \) | 44.94 ± 1.23 \( \text{ab} \) |
| 14   | 38.30 ± 1.55 \( \text{ac} \) | 39.35 ± 1.23 \( \text{ab} \) | 40.33 ± 1.01 \( \text{bc} \) | 41.57 ± 2.13 \( \text{bb} \) | 40.08 ± 1.16 \( \text{bc} \) | 40.36 ± 1.41 \( \text{bb} \) |
| 21   | 36.08 ± 0.50 \( \text{ad} \) | 37.01 ± 1.13 \( \text{bc} \) | 37.14 ± 1.13 \( \text{bd} \) | 37.77 ± 0.95 \( \text{bc} \) | 37.67 ± 1.22 \( \text{bd} \) | 38.50 ± 1.11 \( \text{cc} \) |
| 0    | -13.25 ± 0.35 \( \text{aA} \) | -12.96 ± 1.08 \( \text{aA} \) | -13.64 ± 0.73 \( \text{aA} \) | -13.83 ± 1.28 \( \text{aA} \) | -13.08 ± 0.61 \( \text{aA} \) | -13.51 ± 0.96 \( \text{aA} \) |
| 7    | -10.50 ± 0.54 \( \text{b} \) | -10.44 ± 1.55 \( \text{b} \) | -10.89 ± 1.21 \( \text{b} \) | -10.97 ± 0.66 \( \text{b} \) | -11.91 ± 0.70 \( \text{b} \) | -11.89 ± 0.89 \( \text{ab} \) |
| 14   | -5.40 ± 1.07 \( \text{cc} \) | -5.87 ± 0.42 \( \text{cc} \) | -6.23 ± 0.28 \( \text{bc} \) | -6.84 ± 0.40 \( \text{bc} \) | -7.14 ± 0.60 \( \text{bc} \) | -6.79 ± 0.37 \( \text{bc} \) |
| 21   | 2.06 ± 0.49 \( \text{dD} \) | 2.02 ± 0.56 \( \text{dD} \) | -1.74 ± 0.51 \( \text{cD} \) | -4.62 ± 0.37 \( \text{bD} \) | -5.27 ± 0.58 \( \text{bD} \) | -6.57 ± 0.87 \( \text{ac} \) |

The results are expressed as mean ± standard deviation. Different lowercase letters in the same row indicate significant differences \( (p < 0.05) \) between the treatments. Different capital letters in the same column indicate significant differences \( (p < 0.05) \) between each treatment regarding time.
The pH values (Table 2) increased significantly ($p < 0.05$) in all treatments with time. On day 21, C1 and C2 exhibited pH values of 4.51 ± 0.01 and 4.50 ± 0.01, respectively, while DN10 exhibited the most acidic pH (4.22 ± 0.01), indicating that the rate of maturation was reduced when the fruits were coated.

### Table 2. Physicochemical parameters in tomato fruits coated with nanoemulsion during storage.

| Days | C1          | C2          | DN2.5       | DN5        | DN10       | DN20       |
|------|-------------|-------------|-------------|------------|------------|------------|
| 0    | 4.12 ± 0.01 | 4.14 ± 0.01 | 4.13 ± 0.01 | 4.11 ± 0.02| 4.13 ± 0.02| 4.12 ± 0.01|
| 7    | 4.23 ± 0.00 | 4.08 ± 0.01 | 4.24 ± 0.01 | 4.18 ± 0.01| 4.15 ± 0.01| 4.15 ± 0.01|
| 14   | 4.37 ± 0.01 | 4.18 ± 0.03 | 4.31 ± 0.01 | 4.16 ± 0.01| 4.17 ± 0.02| 4.35 ± 0.02|
| 21   | 4.51 ± 0.01 | 4.50 ± 0.01 | 4.42 ± 0.01 | 4.23 ± 0.04| 4.22 ± 0.01| 4.43 ± 0.01|

The results are expressed as mean ± standard deviation. Different lowercase letters in the same row indicate significant differences ($p < 0.05$) between the treatments. Different capital letters in the same column indicate significant differences ($p < 0.05$) between each treatment regarding time.

The titratable acidity decreased with the storage time in all the treatments (Table 2). On day 21, the DN5, DN10, and DN20 fruits exhibited the highest acidity values (0.47 ± 0.02, 0.48 ± 0.01, and 0.49 ± 0.02, respectively) compared with the C1 (0.38 ± 0.01) and C2 (0.41 ± 0.01) ones, with lower citric acid contents after the evaluation.

Table 2 reveals an increase in the total soluble solid (TSS) contents of all the treatments with respect to the storage time ($p < 0.05$). The controls (C1 and C2) exhibited the highest values on day 21 (4.55 ± 0.05 and 4.50 ± 0.01, respectively) with respect to the coated fruits (4.40 ± 0.17, 4.30 ± 0.10, 4.27 ± 0.06, 4.15 ± 0.05 for DN2.5, DN5, DN10, and DN20, respectively), which correlates with the pH and titratable acidity results.

### 3.3. Bioactive Compounds and Antioxidant Activity

The ascorbic acid content of the tomato fruits (Figure 3) decreased mainly in the control groups (C1 and C2) and the group with the lowest nanoemulsion concentration (DN2.5); their initial ascorbic contents, 24.67 ± 0.58, 25.00 ± 0.00, and 25.83 ± 1.44 mg of ascorbic acid/100 mL decreased to 14.17 ± 1.04, 15.00 ± 0.00, and 15.33 ± 0.58 mg/100 mL on day 21 of the evaluation, respectively. Comparatively, the coated fruits at 5%, 10%, and 20% preserved their ascorbic acid contents better because they exhibited reduced maturation rates.

Regarding the quantification of the total phenols (Table 3), significant differences ($p < 0.05$) were observed in all the treatment groups. The phenol concentrations of DN2.5 and DN20 (238.80 ± 8.33 and 251.45 ± 5.43 mg GAE/100 g, respectively) were higher on day 14 of the evaluation; it subsequently decreased to 157.31 ± 2.45 and 182.62 ± 6.50 mg GAE/100 g on day 21. Moreover, C1 exhibited the lowest values on day 21 (119.97 ± 1.93 mg GAE/100 g).
The results are expressed as mean ± standard deviation. Different lowercase letters in the same row indicate significant differences between the treatments. Different capital letters in the same column indicate significant differences between each treatment regarding time.

Table 3. Quantification of bioactive compounds and antioxidant capacity in tomato fruits during storage.

| Days | C1            | C2            | DN2.5          | DN5            | DN10           | DN20           |
|------|---------------|---------------|----------------|----------------|----------------|----------------|
| 0    | 130.46 ± 6.42 | 126.14 ± 3.85 | 141.88 ± 2.98  | 153.30 ± 3.74  | 152.69 ± 1.60  | 151.45 ± 5.43  |
| 7    | 146.30 ± 8.07 | 154.32 ± 5.35 | 143.21 ± 2.33  | 214.20 ± 1.41  | 195.99 ± 7.01  | 203.09 ± 2.33  |
| 14   | 116.88 ± 2.83 | 139.10 ± 6.17 | 238.80 ± 8.33  | 193.73 ± 1.07  | 212.56 ± 6.17  | 215.45 ± 5.43  |
| 21   | 119.97 ± 1.93 | 148.06 ± 8.07 | 157.31 ± 2.45  | 171.51 ± 5.27  | 174.24 ± 6.50  | 182.62 ± 6.50  |

Figure 3. Vitamin C content in tomato fruits coated with nanoemulsion during storage at 6 °C.
All the treatments exhibited increased flavonoid contents from day 1 of the evaluation; the highest flavonoid contents were observed in the nanoemulsion–coated fruits (Table 3), i.e., DN20 exhibited the highest flavonoid content on day 21 (92.17 ± 1.64 mg QE/100 g) and C1 exhibited the lowest content during the entire test.

The tannin content exhibited differences ($p < 0.05$) in all the treatments with respect to the storage time. However, no difference was observed between the coated treatment groups on day 21 (Table 3). A greater loss in the tannins content was observed in the control fruits, which started the tests with a concentration of 45.17 ± 0.67 mg CE/100 g and ended it with 19.38 ± 0.22 mg CE/100 g.

Regarding the antioxidant activities, Table 3 presents the percentages of inhibitions of the DPPH radical in the tomato fruits with respect to the storage time at different nanoemulsion concentrations. DN20 inhibited up to 48.19 ± 0.95% of the antioxidant activity of the tomato fruits on day 21, which was higher than those of C1 (39.52 ± 0.30%) and C2 (38.14 ± 0.76%).

Significant differences ($p < 0.05$) were observed in the percentage inhibition of the ABTS radical in all the treatments. There was a greater inhibition in the DN20-coated fruits (30.16 ± 1.10%) from day 0, and this trend increased till the end of the evaluation, indicating that C2 exhibited the lowest radical inhibition percentage (22.40 ± 0.83%). Notably, the antioxidant activities, as well as bioactive compound contents of all the treatment groups, exhibited decreases in their results after the analyses owing to the senescence of the fruits. However, the nanoemulsion coatings managed to delay it.

### 3.4. Histological Evaluation

Figure 4 shows the changes in the pericarp cells of the tomato fruits with respect to the storage time at different concentrations of the nanoemulsion. On day 0, all the treatment groups exhibited similar coloration (green); However, C1, C2, and DN2.5 exhibited increased adhesion of the red colour on day 14, owing to the action of Safranin-O. The most representative changes, during which the nanoemulsion coatings (DN10 and DN20) allowed the slower maturation of the cells compared with C1, C2, and DN2.5, which exhibited more red-stained cells, occurred on day 21.

![Figure 4](image-url). Histological evaluation of the pericarp of tomato fruits coated with nanoemulsion during storage. The columns indicate the different treatment (Without coating (C1); only with coating of mineral oil suitable for food (C2); with the nanoemulsion that was diluted to 2.5% (DN2.5), 5% (DN5), 10% (DN10), and 20% (DN20) in the mineral oil suitable for food use) and the rows indicate the different days of analysis (0, 14, and 21 days).
4. Discussion

4.1. Droplet Size and $\zeta$ Potential of the Nanoemulsion

According to the McClements’ parameters [33], the emulsion can be considered a nanoemulsion because it exhibited an adequate droplet size (<100 nm), a translucent appearance, and stability to gravitational separation. Owing to these benefits, nanoemulsions have exhibited a trend in product development since they ensure an excellent distribution in the product for which they were designed [17]. Pérez-Soto et al. [34] reported that the encapsulation of bioactive compounds in nanoemulsions is an effective mechanism of preserving them owing to the various benefits, specifically highlighting the droplet size and stability with time.

4.2. Physico-Chemical Characterization of the Coated Fruits

The weight losses in fresh fruits and vegetables are mainly due to the loss of water via the difference between the water-vapour pressure of the atmosphere and the transpiration surface of the food [35,36]; this is associated with rapid metabolism; thus, an improved degradation of the cell wall and enhanced permeability of the membrane would ensure the easy evaporation of water from the cell [37]. The decrease in the weight loss in the tomato fruits was attributed to the nanoemulsion, which acted as a semi-permeable barrier against gases and moisture [38]. A similar result was reported by Ali et al. [39] who evaluated a gum arabic-based coating in ripe green tomatoes and observed a lower weight loss in the fruits with the coating than those without.

The change in the firmness of the fruits during ripening was attributed to the solubilization of the pectic substances in the cell due to the activity of polygalacturonase and other enzymes [40]. Nawab et al. [41] applied a mango starch coating to tomato fruits and observed that the coating availed a good barrier against gases; therefore, the low and high levels of $O_2$ and $CO_2$, respectively, in the fruit limited the activity of these enzymes and maintained the firmness of the fruits during storage, indicating that the nanoemulsion containing the bioactive compounds of orange essential oil and xoconostle is an effective barrier for preventing the loss of firmness.

Colour is the most significant indicator in tomato fruits [39], and similar results regarding this parameter were reported by Zapata et al. [42] when employing alginate and zein coatings. Das et al. [43] reported that the degradation of the green pigment of chlorophyll and an accumulation of carotenoids, as well as an increase in lycopene, accounted for the red coloration. Similar results were reported by Abebe and Tola [44] who observed reductions in the colour and ripening of tomato fruits containing chitosan and pectin coatings. Cenobio-Galindo et al. [22] employed a nanoemulsion to coat avocado fruits and observed that the application of this type of coating could directly influence the colour, thereby impacting the ripening speed since the changes in the pigments became evident during the maturation and since the pigments could be degraded (as in chlorophyll) or synthesized (as in various carotenoids).

According to Shahnawaz et al. [45], the fruit possessed a reserve source of organic acids during ripening; with increasing storage days, these organic acids were transformed into sugars, which were utilized for metabolic processes, thus reducing the acidity of the medium and increasing the pH value. Salas-Méndez et al. [16] determined the effect of coating tomatoes with a thin film containing alginate and chitosan and observed that the pH increased with time owing to natural ripening processes. Further, a gradual increase was observed in the pH of the coated fruits, which indicated less-accelerated metabolic processes.

The changes observed in the titratable acidity result correspond to those observed for the pH since the organic acids are utilized as substrates in the respiration process during maturation [43,46]. Similar pH and titratable acidity results were obtained when apples were coated with nanoemulsions containing $\alpha$-tocopherol and cactus mucilage [19]. The results were attributed to the changes in the respiratory activity of the fruits.
The increase in the TSS values agree with those reported by Shahnawaz et al. [45] and Yao et al. [47]; they are a function of the changes in the structures of the polysaccharides. Cenobio-Galindo et al. [22] observed that the TSS values correspond to the obtained pH values (as in this work) avocado fruits were coated with a nanoemulsion because the complex molecules in the fruits were degraded in simple sugars during the metabolic processes accompanying ripening.

4.3. Bioactive Compounds and Antioxidant Activity

Sablani et al. [48] reported that the average ascorbic acid content of tomato fruits is 23 mg/100 g. Our results agree with those reported by Moneruzzaman et al. [49] regarding tomato fruits that were evaluated during three maturation stages. The fruits with the highest ascorbic acid content corresponded to that approaching physiological maturity. It was observed that this ascorbic acid concentration decreased as the maturation progressed. Mandal et al. [50] applied chitosan-, wax-, and kaolin-based coatings to tomato fruits to evaluate their shelf-life characteristics. From day seven, they observed a decrease in the concentration of the acid in the fruits that were not coated; the concentration on day 14 decreased further, indicating the high ascorbic acid content of this tomato fruit. However, its preservation was compromised by its susceptibility to rapid oxidation, and a decrease in the content of this compound is evident of senescence.

Tomato fruits attract enormous attention owing to their beneficial effects on human health, in turn owing to their contents of naturally occurring bioactive compounds, such as phenolic compounds [1]. Davila-Aviña et al. [51] studied the effect of coating tomatoes during their shelf life on their bioactive compounds; they observed that the phenolic content increased because the coatings generated abiotic stress, which corresponded to a modification/increase in the production of the secondary metabolites, in the fruits. The results obtained here correspond to those reported by Toor and Savage [52] who evaluated the phenolic compounds in tomato fruits at different temperatures (7, 15, and 25 °C). They observed that the phenolic compound content increased during the first days of the evaluation, after which they decreased at the end of the storage.

Davila-Aviña et al. [51] evaluated the effect of coating tomato fruits and observed that the generated stress also impacted the increase in the flavonoid content, indicating that the increase in the phenolic compounds, such as flavonoids, could be promoted by the activation of the phenylalanine ammonia lyase (PAL) enzyme under stress conditions. Pagni et al. [53] evaluated the effect of a chitosan coating on the concentration of various flavonoids in tomato fruits and found that the quercetin and rutin concentrations increased, while the kaempferol one decreased during the storage.

A decrease in the total tannin content with the progressing maturity has been reported [54]. Sellami et al. [55] evaluated the phenolic compound, flavonoid, and tannin contents of tomato fruits that were grown in protected agriculture; they observed that the production and accumulation of bioactive compounds in these fruits were affected by different factors, such as coatings or chemical treatments.

The consumption of tomatoes promotes good health because the fruit is rich in compounds, such as Vitamins A, C, and E, as well as other bioactive compounds, including carotenoids and phenolic compounds [56]. The use of coatings on fresh vegetables is associated with increased antioxidant activity [1]; therefore, the application of edible coatings could significantly impact the metabolism of the fruits since a micro-atmosphere, which is due to the gas exchange that continues during ripening, is generated by the accumulation of various compounds, such as acetaldehyde, that could induce antioxidant activity [51]. Ali et al. [6] reported a similar result in which tomato fruits, which were coated with a gum-arabic nanoemulsion, preserved the antioxidant activity of the fruit during 20 storage days.

During the ripening of tomatoes, its antioxidant activity increases mainly because of factors, such as the concentrations of carotenoids and vitamins, such as Vitamins C and E [57,58]. Post-harvest treatments, such as the application of coatings, could induce
mechanisms, such as triggering the antioxidant mechanism of the fruit, which affect the metabolism of the fruits, since the activation of the antioxidant system is a response to post-harvest stress [52]. Further, essential oils, such as those in the nanoemulsion employed in this work, could act as signalling compounds, which trigger the signal of mild stress in the fruits. However, the bioactive compounds in the nanoemulsion concurrently protect them from accelerated ripening [59]. Guil-Guerrero and Rebolloso-Fuentes [60] evaluated the antioxidant activities of eight tomato varieties and observed that the results varied according to the variety of the fruit and the test method employed for its quantification.

4.4. Histological Evaluation

The observed colour changes (from green to red) correspond to the maturation of the fruits since there is information on the affinity of safranin for the secondary walls, especially for lignin [61]. Lopes-Carvalho et al. [62] evaluated the chitosan-based coating of melon and observed that it improved the cell structure and decreased the hydrolyase activity of the cell wall by acting as a physical barrier for gas exchange, thus decreasing the respiration rate of the fruit. Cenobio-Galindo [22] evaluated the effect of a nanoemulsion on the shells of avocado fruits and observed that the highest lignification occurred in the shell of the fruits that were not coated, and this indicated that the change in the colour of the peel corresponded to maturation, as well as corroborate the complementary parameters, such as weight loss and firmness.

5. Conclusions

The application of coatings is a novel strategy for stably maintaining bioactive compounds because of the interesting results that have been achieved, as demonstrated by the nanoemulsion in this work. It is an original strategy for managing bioactive compounds. The best results were obtained in the fruits, which were coated with the nanoemulsion; the DN10 and DN20 treatments were the most effective, exhibiting a decrease in the weight loss percentage, improved firmness, and physicochemical parameters, such as acidity and TSS. Additionally, the ascorbic acid, as well as bioactive compound contents, increased with the addition of the nanoemulsion. At the cellular level, the nanoemulsion decreased the lignification of the pericarp, indicating that the rate of ripening of the fruits was lowered. A nanoemulsion, as a coating, is an effective alternative for preserving the postharvest quality of tomato fruits, thereby increasing their shelf life.

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