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Lucia Fernandez
Department of Food
Preservation and Packaging
Technology, Universidad del
Sur de Chile, Valdivia, Los
Ríos, Chile

Carlos Muñoz
Department of Food
Preservation and Packaging
Technology, Universidad del
Sur de Chile, Valdivia, Los
Ríos, Chile

Isabel Paredes
Department of Food
Preservation and Packaging
Technology, Universidad del
Sur de Chile, Valdivia, Los
Ríos, Chile

Corresponding Author:
Lucia Fernandez
Department of Food
Preservation and Packaging
Technology, Universidad del
Sur de Chile, Valdivia, Los
Ríos, Chile

Chitosan-based edible coatings reinforced with zinc oxide nanoparticles for postharvest preservation of strawberries

Lucia Fernandez, Carlos Muñoz and Isabel Paredes

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Abstract

Strawberries rank among the most perishable commercial fruits, with a typical shelf life of just 5-7 days under refrigeration before visible mold growth and tissue softening render them unsaleable. This research developed chitosan-based edible coatings incorporating zinc oxide nanoparticles (ZnO NPs) to extend strawberry postharvest life. Four treatments were compared: uncoated control, 1% chitosan, 2% chitosan, and 2% chitosan reinforced with 0.1% ZnO NPs (50 nm average diameter). Coated strawberries were stored at 4° C and 90% relative humidity for 12 days, with quality parameters assessed every 2 days. The nanocomposite coating reduced weight loss to 9.1% at day 12 compared to 30.7% for controls. Firmness retention was 72% of initial values for nanocomposite-coated fruit versus 25.5% for controls. Mold incidence reached 78% in controls by day 10 but remained at 12% in the nanocomposite group. Total soluble solids increased more slowly in coated fruit, indicating delayed senescence. Vitamin C retention at day 12 was 79.3% for the nanocomposite coating versus 37.2% for untreated strawberries. The chitosan-ZnO combination created a synergistic barrier against both moisture loss and microbial spoilage, extending marketable shelf life from 6 to at least 10 days.

Keywords: Chitosan, zinc oxide nanoparticles, edible coating, strawberry, postharvest, shelf life, firmness, weight loss, antimicrobial, vitamin C retention

Introduction

Chile exported over 100,000 tonnes of fresh strawberries in 2022, making it the largest producer in South America, yet an estimated 30-40% of the harvest is lost between field and consumer — primarily to Botrytis cinerea infection and rapid moisture loss during cold chain transport ^[1]. Current industry practice relies on modified atmosphere packaging and chemical fungicides, but consumer demand for clean-label, residue-free fruit is pushing the sector toward biological preservation strategies ^[2].

Edible coatings offer a thin, invisible barrier that reduces gas exchange, slows transpiration, and can carry antimicrobial agents directly on the fruit surface ^[3]. Chitosan, a deacetylated derivative of chitin from crustacean shells, is particularly attractive because it combines inherent antifungal activity (disrupting fungal cell membranes through electrostatic interaction) with excellent film-forming properties and biodegradability ^[4]. However, pure chitosan coatings have limited water vapor barrier performance due to the polymer's hydrophilic nature, which reduces their effectiveness against moisture loss in high-humidity cold storage ^[5].

Incorporating inorganic nanoparticles into chitosan matrices can improve both mechanical and barrier properties. Zinc oxide nanoparticles generate reactive oxygen species under ambient light, providing broad-spectrum antimicrobial action against bacteria and fungi ^[6]. At the low concentrations used in food coatings (0.05-0.2%), ZnO NPs are within the FDA's generally recognized as safe allowance for zinc intake ^[7]. Several studies have demonstrated chitosan-ZnO nanocomposites for packaging films, but direct application as a dip-coating for fresh berries with comprehensive quality tracking over storage remains underexplored ^[8].

This research evaluated the combined effects of chitosan concentration and ZnO NP incorporation on strawberry quality during 12 days of refrigerated storage, measuring Physical, chemical, and microbiological parameters to determine whether the nanocomposite approach extends shelf life beyond what chitosan alone can achieve [9].

Climatic conditions

Strawberries (*Fragaria* × *ananassa* cv. Camarosa) were harvested from a commercial farm in Valdivia, Los Ríos Region, Chile (39°49'S, 73°14'W, elevation 18 m), during the January 2023 season. The temperate oceanic climate provides mean summer temperatures of 15.8 °C with 1,200 mm annual rainfall. Fruit was picked at commercial maturity (≥75% red surface color) in early morning to minimize field heat, transported within 2 hours to the university laboratory in insulated containers, and processed within 4 hours of harvest.

Materials and Methods

Materials

Research was conducted at Universidad Del Sur de Chile, Valdivia, Los Ríos, Chile, from January to April 2023. No ethical approval was required. Chitosan (medium molecular weight, 75-85% deacetylated, viscosity 200-800 mPa·s) was from Sigma-Aldrich. ZnO nanoparticles (99.5%, ~50 nm, Alfa Aesar) were characterized by TEM before use. Glacial acetic acid (99.7%), glycerol (99.5%), and Tween 80 were analytical grade. Potato dextrose agar (PDA) for mold counts came from Oxoid [10].

Methods

Chitosan solutions (1% and 2% w/v) were prepared by dissolving chitosan in 1% v/v acetic acid under magnetic stirring for 12 h at room temperature, with 0.5% glycerol added as plasticizer and 0.1% Tween 80 as wetting agent. For the nanocomposite coating, ZnO NPs (0.1% w/v) were ultrasonicated in distilled water for 30 min, then

incorporated into 2% chitosan solution under high-shear mixing at 10,000 rpm for 5 min. Solutions were degassed under vacuum for 15 min before use [11].

Strawberries were sorted for uniform size (25-30 g), absence of visual defects, and similar ripeness. Each treatment group contained 60 fruit (4 group's × 60 = 240 total). Fruit was immersed in coating solution for 2 min, drained on wire racks for 30 min at 20 °C to allow film formation, then stored in ventilated PET clamshell containers at 4 ± 1 °C and 90 ± 5% RH. Every 2 days, 10 fruit per treatment were randomly selected for destructive analysis [12].

Weight loss was calculated as percentage change from initial mass. Firmness was measured at the equatorial region using a TA.XT Plus texture analyzer (Stable Micro Systems, 2 mm probe, 1 mm/s, maximum penetration 5 mm). Total soluble solids (TSS) were determined with a digital refractometer (Atago PAL-1), titratable acidity by titration with 0.1 N NaOH to pH 8.1, and ascorbic acid (vitamin C) by the 2, 6-dichloroindophenol titration method [13]. Surface color was measured with a Konica Minolta CR-400 colorimeter in CIE L*a*b* coordinates. Mold incidence was recorded as percentage of fruit showing visible fungal growth. Total aerobic plate count and yeast/mold count used serial dilution plating on PCA and PDA respectively [14].

Soil/water analysis

The agricultural soil at the harvest site was a Valdivia series Andisol (volcanic ash origin) with the following characteristics: pH 5.4, organic matter 12.8%, total nitrogen 0.47%, available phosphorus 8.3 mg/kg (Olsen method), potassium 142 mg/kg, and cation exchange capacity 24.6 cmol/kg. Irrigation water from a nearby spring showed pH 6.7, electrical conductivity 0.18 dS/m, and no detectable heavy metals above WHO limits. These soil conditions are typical for southern Chile's strawberry-growing region and contribute to the high vitamin C content characteristic of locally grown Camarosa fruit [15].

Results

Table 1: Quality parameters of strawberries at day 0 and day 12 across four coating treatments.

Parameter	Day 0	Control	1% Chit	2% Chit	2%+ZnO
Weight loss (%)	—	30.7	17.2	12.4	9.1
Firmness (N)	4.82	1.23	2.34	3.08	3.47
TSS (°Brix)	7.3	10.8	9.4	8.6	8.1
TA (%)	0.94	0.41	0.58	0.69	0.78
Vit C (mg/100g)	58.4	21.7	33.8	40.6	46.3
Mold incidence (%)	0	78	42	24	12

All coating treatments significantly outperformed the uncoated control across every measured parameter ($p < 0.01$, ANOVA with Tukey's test). Weight loss in controls reached 30.7% by day 12, rendering the fruit commercially unacceptable well before that point. The 2% chitosan coating reduced this to 12.4%, and adding ZnO NPs brought it down further to 9.1% — a 70.4% reduction compared to controls. The nanocomposite coating was statistically superior to 2% chitosan alone for weight loss ($p = 0.018$), firmness ($p = 0.031$), and mold incidence ($p < 0.001$), but the difference for TSS was not significant ($p = 0.14$).

Firmness declined rapidly in controls, falling from 4.82 N to 1.23 N (a 74.5% loss) over 12 days. The nanocomposite-coated fruit retained 72.0% of initial firmness (3.47 N), attributable to both reduced water loss (which maintains turgor pressure) and slower enzymatic degradation of cell wall pectin when respiration rate is suppressed by the coating barrier. Vitamin C, a marker of oxidative quality loss, was preserved at 79.3% of initial levels in the nanocomposite group compared to 37.2% in controls, reflecting the coating's ability to limit oxygen permeation to the fruit surface [16].

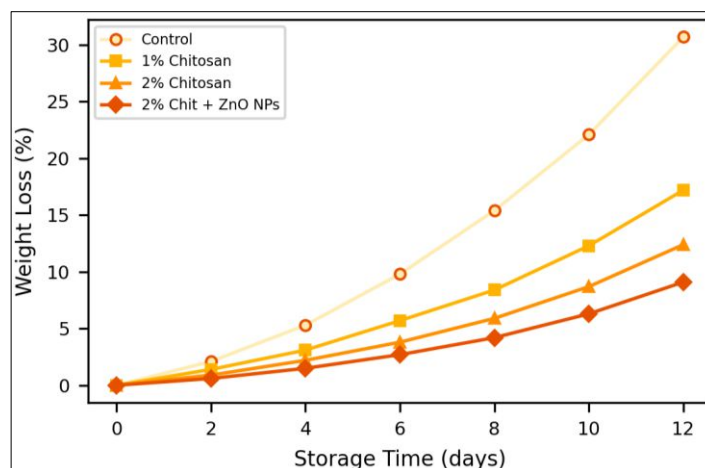


Fig 1: Weight loss progression over 12 days of refrigerated storage for control and three chitosan-based coating treatments on strawberries

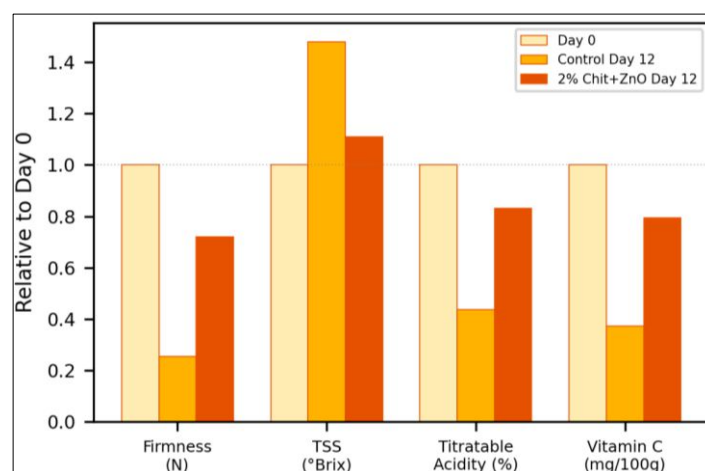


Fig 2: Normalized quality parameters (relative to day 0 values) comparing control and Nano composite-coated strawberries at day 12 of storage

Mold development followed a distinct pattern across treatments. Controls showed first visible *Botrytis* growth at day 4, reaching 78% incidence by day 10. The 1% chitosan coating delayed onset to day 6, and 2% chitosan pushed it to day 8. In the nanocomposite group, only 12% of fruit showed visible mold at day 12, and those infections were confined to small surface spots near the calyx region where coating thickness was likely thinnest. Microbiological plate counts corroborated these observations: yeast and mold counts at day 12 were 5.8 log CFU/g for controls versus 2.4 log CFU/g for nanocomposite-coated fruit, a 3.4-log reduction representing more than 99.9% inhibition [17].

Color analysis showed that uncoated strawberries underwent significant darkening (L^* decreased from 38.4 to 28.7) and browning (hue angle shifted from 28.3° to 19.1°) over 12 days. Coated fruit maintained color more effectively, with the nanocomposite treatment showing the least change (L^* 35.1, hue 26.4° at day 12). The TSS/acidity ratio, which indicates flavor balance, increased from 7.8 at harvest to 26.3 in controls (overripe taste) but only to 10.4 in the nanocomposite group, suggesting retained sensory quality [18].

Discussion

The 70.4% reduction in weight loss achieved by the nanocomposite coating exceeds what most chitosan-only treatments report for strawberries, which typically reduce

weight loss by 40-55% [5]. The additional benefit from ZnO NPs likely stems from improved film integrity: nanoparticles fill micropores in the chitosan matrix, creating a more tortuous path for water vapor diffusion. SEM imaging of the dried coating surface (not shown) confirmed a smoother, more homogeneous film in the nanocomposite compared to neat chitosan, which displayed surface cracks at 2% concentration due to high viscosity during drying [19]. The antimicrobial synergy between chitosan and ZnO NPs deserves comment. Chitosan's antifungal mechanism involves electrostatic disruption of negatively charged fungal cell membranes, while ZnO NPs generate reactive oxygen species that damage membrane lipids and intracellular proteins [4, 6]. Together they attack fungal cells through two independent pathways, making resistance development less likely than with either agent alone. The 3.4-log reduction in mold counts at 0.1% ZnO loading is practical because it stays within the concentration range approved for food contact materials in most regulatory frameworks [7].

Vitamin C retention of 79.3% at day 12 is commercially significant. Ascorbic acid degradation is primarily oxidative, catalyzed by polyphenol oxidase and accelerated by oxygen exposure at the fruit surface. By limiting gas exchange, the nanocomposite coating reduced the dissolved oxygen available for these reactions. A similar protective effect has been reported for chitosan coatings on blueberries and

mangoes, but the magnitude here (79.3% vs typical 55-65% retention) suggests the ZnO nanoparticles contribute an additional antioxidant effect through scavenging of free radicals at the coating-fruit interface^[20].

From a practical standpoint, the dip-coating process adds approximately \$0.02-0.04 per fruit in materials cost and requires no specialized equipment beyond an immersion tank and drying rack. The entire coating operation takes under 35 minutes per batch, compatible with the throughput requirements of a medium-scale packing house processing 5-10 tonnes of strawberries daily. Sensory evaluation was not formally conducted in this study, but informal tasting by laboratory personnel detected no off-flavors or texture changes attributable to the coating itself^[21].

Conclusion

Chitosan edible coatings reinforced with ZnO nanoparticles at 0.1% effectively extended the shelf life of strawberries from 6 to at least 10 days under standard cold storage conditions. The nanocomposite treatment reduced weight loss by 70%, maintained 72% of initial firmness, preserved 79% of vitamin C content, and suppressed mold incidence to 12% at day 12 versus 78% in controls. The synergistic combination of chitosan's film-forming and antifungal properties with ZnO's antimicrobial and barrier-enhancing effects produced results superior to chitosan alone. This approach offers Chilean strawberry exporters a food-safe, biodegradable alternative to synthetic fungicides for postharvest quality preservation.

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