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Research Article

The application of a spray-coated Nano-CeO_2-Reinforced chitosan nanocomposite coating for banana preservation

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ABSTRACT

Post-harvest fruit spoilage results in significant economic losses and raises food safety concerns; these issues have a profound impact on both human health and the environment. Bananas are rich in nutrients, but their high perishability is a major obstacle that has limited their export. This study investigates the effectiveness of a nanocomposite spray coating based on chitosan (CH) integrated with both hydrothermally prepared CeO_2 ($hCeO_2$) and solvothermally prepared CeO_2 ($sCeO_2$) at extending the shelf life of post-harvest bananas. The preservative capabilities of this nanocomposite spray coating were assessed using visual attributes, weight and water loss, firmness, total soluble solids, total acidity, and pH during storage. The results highlight the effectiveness of CH-$sCeO_2$ at limiting the weight loss and softening of bananas, delaying the climacteric peak, and slowing down physicochemical changes in comparison with CH-$hCeO_2$, Kadozan, and chitosan coatings, as well as uncoated fruit. Specifically, CH-$sCeO_2$ applied using the spray-coating method extended the shelf life of post-harvest bananas to 8 days at 25 °C and 64 % RH, providing an alternative approach to enhancing the storability of perishable fruits.

Key words: Chitosan, agricultural product preservation, biofilm, biodegradability

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INTRODUCTION

Fresh bananas contribute significantly to overall health due to their rich nutrient profile and natural bioactive compounds[1]. According to the FAO, Asia produces 54.4% of the world's banana supply, with an average consumption of approximately 12 kg/person/year[1]. Bananas are an important source of reducing sugars, fiber, vitamins (B3, B6, B12, C, and E), phenolic compounds, flavonoids, carotenoids, and amino acids. Its peel constitutes 30–40% of the fruit's weight and contains high levels of fiber, pectin, protein, lipids, and trace minerals; its chemical composition varies with ripening stage[2]. Specifically, its chemical composition changes significantly across the three main ripening stages: green (stage 1), yellow-green (stage 5), and yellow with brown spots (stage 7). These compositional changes affect the physical and chemical properties of the peel. Bananas have a high moisture content (70–80%) and are mildly acidic due to malic and oxalic acids. As climacteric fruits, bananas are highly perishable because continuous respiration accelerates ripening, leading to eventual spoilage.

Post-harvest techniques used to extend the storability of bananas include low-temperature storage, chemicals, ethylene-inhibiting gases, and edible coatings. Although low-temperature storage reduces respiration and microbial growth, temperatures below 13 °C can damage the peel, leading to discoloration and loss of flavor. Chemical agents such as nitrous oxide or salicylic acid can delay ripening, but carry toxicity risks that could affect consumer health (including nervous system damage) if allowed to accumulate[3]. 1-Methylcyclopropene (1-MCP) is an efficient ethylene inhibitor that helps extend the shelf life of the fruit, but it is prohibitively expensive and difficult to implement on large scales.

In recent years, edible coatings have become popular because they form a protective film, regulate gas exchange, reduce water loss, and lower respiration rates without introducing toxicity[4]. Chitosan is a natural polysaccharide obtained from the deacetylation of chitin, which is found in shrimp and crab shells as well as certain fungi. The chitosan structure consists of D-glucosamine and N-acetyl-D-glucosamine units linked by β-(1→4)-glycoside. In acidic media, chitosan becomes polycationic, giving it strong film-forming abilities as well as antimicrobial, antifungal, and antioxidant properties. These characteristics, combined with its high biodegradability, make chitosan a common ingredient in food preservation, especially as an edible coating to extend the shelf life of fruits and vegetables[5].

Recent work has incorporated nanoparticles such as ZnO, TiO_2, and Ag to improve the mechanical properties, antimicrobial activity, and gas barrier perfor-

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mance of these chitosan coatings[6,7]. However, some of these particles, notably silver, can raise toxicity concerns if they migrate into food. They may also fail to inhibit ethylene, the hormone that drives ripening and fruit spoilage. Therefore, the identification of low-toxicity nanoparticles for the reinforcement of chitosan coatings is essential.

CeO_2 is a highly stable, water-insoluble material that possesses strong redox properties and is considered safe for human consumption[8]. Its fluorite cubic structure allows for reversible redox transitions between Ce^{3+} and Ce^{+} states, creating oxygen vacancies on the surface of the material that enhance the adsorption and oxidation of ethylene. Indeed, the use of CeO_2 in packaging materials has increased recently as CeO_2 has been reported to be less hazardous than TiO_2 and ZnO[9]; specifically, it is considered to be safe at concentrations below 88 ppm, with no cytotoxic effects in biomedical studies[10]. The addition of CeO_2 into chitosan coating is expected to improve antioxidant capacity, reduce water loss, and decrease ethylene formation, thereby significantly extending the post-harvest shelf life of bananas.

Coating solutions are traditionally applied to fruit skins by dip-coating or spray-coating. Dip-coating involves immersing the fruit in solution for a set period before allowing it to drain, resulting in a uniform film on the surface of the fruit. This method is simple, requires minimal equipment, and the film created evenly covers the entire fruit, making it suitable for small-scale operations. Its main drawbacks include high consumption of the coating solution, low utilization efficiency, and the risk of microbial cross-contamination if the same solution is used for multiple fruits[11]. In contrast, the spray-coating method uses mist-generating equipment to evenly disperse the coating solution onto the surface of the fruit. This technique uses the coating material more efficiently, allows for the precise control of coating thickness, is suitable for large-scale production, and carries a lower risk of cross-contamination[12]. The choice between dip and spray methods has significant economic, environmental, and product-quality consequences.

This study investigates the application of a chitosan/CeO_2 nanocomposite coating to extend the post-harvest shelf life of bananas using the spray-coating technique. To the best of our knowledge, no work has been reported on the use of this chitosan/CeO_2 nanocomposite coating using a spray-coating approach for banana preservation. The effectiveness of this technique was assessed by comparing fresh bananas stored at 20 °C for 8 days under the following conditions: untreated bananas, bananas coated with pure chitosan, bananas treated with a commercial chitosan solution (Kadozan), and bananas coated with the chitosan/CeO_2 nanocomposite. Physiochemical changes such as firmness, weight loss, peel color, total soluble solids, pH, total acidity, and CO_2 production rate were recorded during storage.

MATERIALS AND METHODS

Chemicals

The following chemicals were used in this study: chitosan (Sigma Aldrich, USA), $Ce(NO_3)_3.6H_2O$ (Jiangxi, China), glycerol (Himedia, India), acetic acid 99.7%, n-butanol 99.5%, NaOH 99.5%, and ethanol 97.7% (Sinopharm Chemical Reagent, China).

Synthesis procedure of CeO_2

CeO_2 nanoparticles were synthesized via two methods. For the first method, hydrothermal synthesis[13], 1.92 g of $Ce(NO_3)_3.6H_2O$ is dissolved in 40 mL of distilled water under constant stirring for 30 min. Subsequently, 20 mL of 2M NaOH solution was added dropwise to the solution, forming a white precipitate. The suspension was transferred into a Teflon-lined stainless steel autoclave and dried at 180 °C for 24 h. The mixture was cooled to room temperature (27 °C), and the yellow precipitate was collected by centrifugation and washed repeatedly with 96% ethanol and distilled water until the wash solution reached pH = 7. The prepared sample was dried at 80 °C overnight and then calcined in a muffle furnace at 400 °C for 2 h (heating rate 5 °C/min) to yield $hCeO_2$.

The second method, solvothermal synthesis[14], was investigated due to its simple implementation and low processing temperature. 1.92 g of $Ce(NO_3)_3.6H_2O$ was dissolved in 60 mL of n-butanol under constant stirring for 30 min at room temperature (27 °C). The resulting solution was incubated in an oven at 140 °C for 12 h. After cooling to room temperature, the yellow precipitate was collected by centrifugation and washed repeatedly with ethanol and distilled water. The final product was dried at 80 °C for 12 h to yield solvothermally synthesized CeO_2 ($sCeO_2$) for subsequent characterization.

Synthesis procedure of chitosan/CeO_2 composite

$sCeO_2$ and $hCeO_2$ have previously been shown to intercalate with chitosan coating through hydrogen bonding and electrostatic interactions[15,16], thereby improving the mechanical strength and barrier properties of chitosan-based composites. A coating comprising chitosan (1%, w/v) integrated with $sCeO_2$ and

$hCeO_2$ (1.5%, w/w chitosan weight) exhibited the best overall performance and was selected for use in this study.

The 1% (w/v) chitosan (CH) solution was prepared by dissolving 1 g of chitosan powder in 100 mL of 1% (v/v) acetic acid at room temperature (27 °C). Glycerol (30%, w/w chitosan powder) was added to the chitosan solution under magnetic stirring for 1 h. $sCeO_2$ and $hCeO_2$ were gradually incorporated into the glycerol-plasticized chitosan solution and magnetically stirred for 60 min. The mixture was sonicated for 2 h to improve nanoparticle dispersion and facilitate the intercalation of $sCeO_2$ and $hCeO_2$ within the polymer matrices. The resulting CH-$sCeO_2$ and CH-$hCeO_2$ inoculants were employed in the subsequent preliminary banana preservation experiments.

Banana preservation using the spray-coating method

Bananas were selected for uniform ripeness, size, and weight. The bananas were washed with water to remove impurities and dried at 20 °C. They were then randomly divided into five groups: an uncoated control group, and four groups coated with Kadozan solution, pure chitosan, CH-$hCeO_2$, and CH-$sCeO_2$. The coatings were applied using an Oshima air compressor. 5 mL of coating solution was sprayed evenly onto the surface of the bananas using a hand-held spray gun; the nozzle was held at least 25 cm away from the fruit with an operating pressure of 3 bar. This procedure was repeated three times at 30-minute intervals to ensure a uniform coating on the peel.

Samples were stored at 20 °C and monitored for changes in appearance, browning index, weight loss rate, respiration rate, firmness, total soluble solids, total acidity, and pH in both coated and uncoated bananas.

Procedure for evaluating the physicochemical properties of bananas

Color measurements were performed using a CR-400 colorimeter (Konica Minolta, Japan) calibrated with a standard white plate (Y = 93.8, x = 0.3134, y = 0.3194). Measurements were taken in the CIE L*a*b color space under D65 illumination and standard 2° observer conditions. For each sample, three random points on the surface were measured, and the mean values of L, a, and b were recorded. The browning index (BI) was calculated according to the following equation:

$$BI = \frac{100\times(x-0.31)}{0.17}, with\ x = \frac{a+1.75\times L}{5.645\times L+a-0.012\times b}$$

CO_2 production in bananas with and without coating was measured using a GS6000 CO_2 analyzer (Illinois Instruments Inc.). The bananas were weighed and placed in a sealed 2 L container fitted with a rubber septum at 25 °C. CO_2 concentration was measured after 1 h of incubation. The instrument was operated in infrared (IR) absorption mode over a detection range of 0–100% CO_2 and an accuracy of ±0.2%. Measurements were continuously conducted at room temperature with a flow rate of approximately 100 mL/min. Readings were taken after the signal stabilized; results were expressed as percentage CO_2 concentration (% v/v).

The weight of each banana was measured using an F6001B electrical balance (Huanghua Faithful Instrument Co., Ltd.). The balance has a measurement range of 0.4–610 g, an accuracy of 0.1 g, and a temperature compensation range of 5–25 °C. The weight loss rate was calculated using the following formula:

$$Weight\ loss\ (\%) = \frac{m_{initial\ day}-m_{next\ day}}{m_{initial\ day}} \times 100$$

Fruit firmness was measured using a GY-3 fruit hardness tester (Wenzhou Sanhe Measuring Instrument Co., Ltd., China). The instrument was equipped with a 3-mm diameter stainless-steel probe and operated in the range between 0–20 kgf. Measurements were obtained by inserting the probe into the equatorial region of the fruit at a constant speed until the peel was completely punctured. The maximum force (kgf) required for penetration was recorded as the firmness value and was reported in N.

The total soluble solid (TSS) content of the fruit pulp was measured using a PAL-1 refractometer (Atago Co., Ltd.). The device has a measurement range of 0.0–53.0%, an accuracy of 0.2%, and a temperature compensation range of 10–100 °C with 1 °C accuracy.

Titratable acidity (TA) was measured according to P. R. and K. S. A. Wantat[17]. In brief, 10 g of pulp sample was homogenized with 100 mL of distilled water for 60 s, then filtered through cotton wool. 10 mL of the filtrate was titrated with 0.1 N NaOH using 1% phenolphthalein as an indicator. The titration was stopped when the solution changed from colorless to a stable pink color that persisted for 30 s; the final burette reading was recorded at this point. TA was calculated using equation (10), using 0.067 as the milliequivalent factor for malic acid in bananas.

$$TA\ (\%) = \frac{V_{NaOH}\times C_{NNaOH}\times 0.064\times V_{total\ juice}\times 100}{10g}$$

The pH of the aforementioned filtrate was measured using a HI2211-02 benchtop pH meter (Hanna Instruments Inc.).

RESULTS AND DISCUSSION

Banana images and browning index

Figure 1 shows that all banana groups turned yellow by the second day of storage. Brown spots appeared on banana peels starting from the fourth day onward and developed quickly in the days following. Uncoated fruit was observed to spoil by day 5, while Kadozan- and chitosan-coated fruit spoiled after 6 days. Bananas treated with CH-sCeO$_2$ delayed spoilage until day 8, highlighting the superior performance of this nanocomposite coating.

The browning index (Figure 2 and Table 1) was consistent with these visual changes. In the control sample, the browning index increased rapidly from 87.54 (day 0) to 148.43 (day 5), while the coated samples exhibited slower increases. Among the coated groups, the CH-sCeO$_2$ group increased the slowest, from 80.15 (day 0) to 97.00 (day 5); this was approximately 3.5 times slower than the uncoated bananas. Once again, this demonstrates the effectiveness of the CH-sCeO$_2$ spray coating in limiting polyphenol oxidase activity and slowing phenolic oxidation, which are the primary causes of peel browning [18].

^{abcde}Different letters within the same column indicate statistically significant differences across different days of storage according to the Tukey HSD test ($p < 0.05$).

^{123}Different numbers within the same row indicate statistically significant differences across different coatings during storage according to the Tukey HSD test ($p < 0.05$).

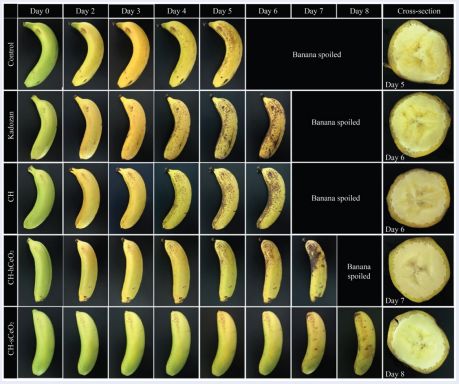

Figure 1: Images of bananas across eight days of storage at 20 °C

Respiration rate of bananas

After harvest, bananas typically increase their respiration rate as they approach ripening [19]. The respiration rate is determined by the amount of CO_2 produced (mg CO_2/kg·h), which is an indicator of metabolic activity based on the following equation:

$$C_6H_{12}O_6 + 6O_2 + 6H_2O \rightarrow 6CO_2 + 12H_2O$$

The control sample and Kadozan-coated bananas exhibited a more rapid increase in respiration rate compared to the other groups, reaching a peak of 352.83 mgCO_2/kg·h and 332.40 mgCO_2/kg·h, respectively, after three days of storage (Figure 3 and Table 2). The bananas sprayed with CH-hCeO$_2$ and CH-sCeO$_2$ exhibited slower respiration rate increases. The CH-hCeO$_2$-coated bananas peaked on day 4 (304.36 mg CO_2/kg·h), while the CH-sCeO$_2$-coated bananas peaked on day 5 (284.25 mg CO_2/kg·h). The delayed respiration peak of the CH-sCeO$_2$-coated bananas compared to the other groups indicates that this coating formed a semi-permeable membrane around the fruit, thereby reducing respiration, limiting ethylene activation, which is the primary hormone that accelerates ripening [18]. These results demonstrate that CH-sCeO$_2$ more effectively slows respiration compared to uncoated or conventionally coated bananas, delaying the ripening and softening.

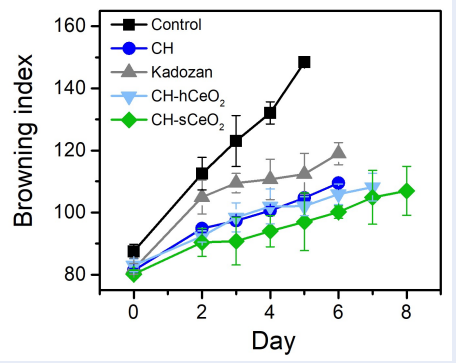

Figure 2: Browning index of bananas across eight days of storage.

Weight loss and the firmness of bananas

Weight loss was observed throughout the storage period due to the naturally perishable nature of bananas. The weight loss was inversely proportional to ripening time, reflecting the extent of moisture and volatile substance loss during storage [20]. In general, weight loss increased with storage time (Figure 4 and Table 2). The control group, as well as the Kadozan- and chitosan-coated groups, exhibited a faster weight loss rate compared to the groups coated with CH-hCeO$_2$ and CH-sCeO$_2$. The control sample lost 11.04% of its weight after 5 days of storage, while the weight loss of

Table 1: Browning index of bananas across eight days of storage.

	Control	Kadozan	CH	CH-hCeO$_2$	CH-sCeO$_2$
Day 0	$87.54^{a,1}\pm2.27$	$81.84^{a,2}\pm1.68$	$81.40^{a,3}\pm0.54$	$82.98^{a,3}\pm2.01$	$80.15^{a,3}\pm1.28$
Day 2	$112.51^{b,1}\pm5.24$	$104.98^{b,2}\pm5.45$	$94.83^{b,3}\pm1.34$	$92.33^{b,3}\pm1.88$	$90.39^{b,3}\pm4.50$
Day 3	$123.06^{bc,1}\pm8.23$	$109.50^{bc,2}\pm3.09$	$97.34^{bc,3}\pm1.39$	$98.45^{bc,3}\pm4.66$	$90.79^{bc,3}\pm7.71$
Day 4	$132.09^{bcd,1}\pm3.58$	$110.68^{bcd,2}\pm6.50$	$100.60^{bcd,3}\pm1.29$	$101.99^{bcd,3}\pm5.60$	$94.02^{bcd,3}\pm5.04$
Day 5	$148.43^{cde,1}\pm0.71$	$112.41^{cde,2}\pm6.61$	$104.75^{cde,3}\pm0.69$	$102.07^{cde,3}\pm3.03$	$97.00^{cde,3}\pm9.29$
Day 6	-	$118.95^{d,2}\pm3.55$	$109.52^{d,3}\pm0.47$	$105.92^{d,3}\pm3.29$	$100.14^{d,3}\pm2.03$
Day 7	-	-	-	$108.23^{d,3}\pm4.50$	$104.89^{d,3}\pm8.70$
Day 8	-	-	-	-	$106.98^{de,3}\pm7.89$

CH-hCeO$_2$ and CH-sCeO$_2$ was 11.21% and 11.17%, respectively, after 6 days of storage. These results indicate that CeO$_2$ nanoparticles incorporated with chitosan coating act as an effective moisture barrier that limits evaporation, which is the primary cause of wilting and weight loss.

Firmness is a key indicator of the freshness and sensory quality of fruits. During ripening, firmness (or softness) is associated with three processes[18,21]: (1) the breakdown of starch into soluble sugars; (2) the degradation of cell walls or the reduction of middle lamella adhesion due to the solubilization of pectic substances; and (3) the movement of water from the peel to the stem during ripening caused by osmosis. In general, the firmness of all banana groups decreased with storage time (Figure 5 and Table 2). The trends were similar to those of the weight loss results: firmness decreases in the control group, Kadozan-, chitosan-, and CH-hCeO$_2$-coated groups were faster than the CH-sCeO$_2$-coated group. The firmness of the control sample dropped from 43.04 N (day 0) to 11.22 N (day 5), while the firmness of the CH-sCeO$_2$ samples was as high as 11.34 N on day 8. These results demonstrate the effectiveness of chitosan coating reinforced with sCeO$_2$ in maintaining the firmness of bananas, slowing the softening process, preserving cellular tissue structure, and supporting postharvest transport and storage.

^{abcdefgh}Different letters within the same column indicate statistically significant differences across different days of storage according to the Tukey HSD test ($p < 0.05$).

^{123}Different numbers within the same row indicate statistically significant differences across different coatings during storage according to the Tukey HSD test ($p < 0.05$).

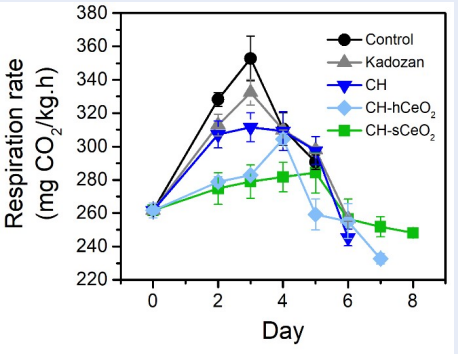

Figure 3: Respiration rate of bananas across eight days of storage.

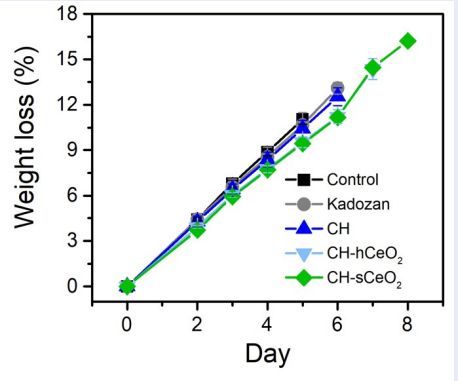

Figure 4: Weight loss rate of bananas across eight days of storage.

Table 2: Changes in respiration rate, weight loss rate, and firmness of bananas across eight days of storage.

		Control	Kadozan	CH	CH-hCeO_2	CH-sCeO_2
Respiration rate ($mgCO_2$/kg.h)	Day 0	$261.60^{a,1}\pm4.42$	$261.60^{a,1}\pm4.42$	$261.60^{a,1}\pm4.42$	$261.60^{a,2}\pm4.42$	$261.60^{a,2}\pm4.42$
	Day 2	$328.20^{cd,1}\pm4.14$	$312.84^{cd,1}\pm6.56$	$307.20^{cd,1}\pm8.10$	$278.81^{cd,2}\pm3.03$	$274.82^{cd,2}\pm9.49$
	Day 3	$352.83^{d,1}\pm13.47$	$332.40^{d,1}\pm7.66$	$311.58^{d,1}\pm8.68$	$282.78^{d,2}\pm1.27$	$278.94^{d,2}\pm9.94$
	Day 4	$310.55^{cd,1}\pm9.78$	$309.87^{cd,1}\pm0.08$	$309.29^{cd,1}\pm11.75$	$304.36^{cd,2}\pm3.38$	$281.70^{cd,2}\pm8.83$
	Day 5	$290.57^{bc,1}\pm4.30$	$297.88^{bc,1}\pm2.24$	$297.56^{bc,1}\pm8.47$	$259.28^{bc,2}\pm9.31$	$284.25^{bc,2}\pm12.05$
	Day 6	-	$256.69^{a,1}\pm1.48$	$245.40^{a,1}\pm5.05$	$255.07^{a,2}\pm10.46$	$256.49^{a,2}\pm11.88$
	Day 7	-	-	-	$232.65^{a,2}\pm3.16$	$251.78^{a,2}\pm6.10$
	Day 8	-	-	-	-	$248.12^{ab,2}\pm3.09$
Weight loss rate (%)	Day 0	$0.00^{a,1}$	$0.00^{a,1}$	$0.00^{a,1}$	$0.00^{a,2}$	$0.00^{a,2}$
	Day 2	$4.43^{b,1}\pm0.09$	$4.43^{b,1}\pm0.38$	$4.29^{b,1}\pm0.34$	$3.92^{b,2}\pm0.10$	$3.73^{b,2}\pm0.03$
	Day 3	$6.80^{c,1}\pm0.24$	$6.58^{c,1}\pm0.51$	$6.42^{c,1}\pm0.35$	$6.04^{c,2}\pm0.17$	$5.94^{c,2}\pm0.11$
	Day 4	$8.88^{d,1}\pm0.27$	$8.56^{d,1}\pm0.64$	$8.36^{d,1}\pm0.50$	$7.75^{d,2}\pm0.23$	$7.71^{d,2}\pm0.11$
	Day 5	$11.04^{e,1}\pm0.32$	$10.67^{e,1}\pm0.80$	$10.42^{e,1}\pm0.55$	$9.54^{e,2}\pm0.36$	$9.43^{e,2}\pm0.12$
	Day 6	-	$13.10^{f,1}\pm0.38$	$12.54^{f,1}\pm0.58$	$11.21^{f,2}\pm0.45$	$11.17^{f,2}\pm0.11$
	Day 7	-	-	-	$14.37^{g,2}\pm0.69$	$14.46^{g,2}\pm0.02$
	Day 8	-	-	-	-	$16.23^{h,2}\pm0.10$
Firmness (N)	Day 0	$43.04^{a,1}\pm0.48$	$43.04^{a,12}\pm0.48$	$43.04^{a,2}\pm0.48$	$43.04^{a,3}\pm0.48$	$43.04^{a,3}\pm0.48$
	Day 2	$21.34^{b,1}\pm0.49$	$22.79^{b,12}\pm0.30$	$24.87^{b,2}\pm0.76$	$29.85^{b,3}\pm0.55$	$29.48^{b,3}\pm0.94$
	Day 3	$17.99^{c,1}\pm0.71$	$18.47^{c,12}\pm0.62$	$18.87^{c,2}\pm0.53$	$21.55^{c,3}\pm1.17$	$23.44^{c,3}\pm0.86$
	Day 4	$14.58^{d,1}\pm0.52$	$15.73^{d,12}\pm0.47$	$16.73^{d,2}\pm0.63$	$18.93^{d,3}\pm0.29$	$21.85^{d,3}\pm0.57$
	Day 5	$11.22^{e,1}\pm0.57$	$11.33^{e,12}\pm0.25$	$11.55^{e,2}\pm0.11$	$17.00^{e,3}\pm1.10$	$17.23^{e,3}\pm0.89$
	Day 6	-	$8.00^{f,12}\pm0.57$	$9.95^{f,2}\pm0.28$	$13.82^{f,3}\pm0.62$	$14.69^{f,3}\pm0.45$
	Day 7	-	-	-	$11.22^{f,3}\pm0.24$	$12.10^{f,3}\pm0.59$
	Day 8	-	-	-	-	$11.34^{f,3}\pm0.34$

Physicochemical properties of bananas

TSS in fruits includes carbohydrates, organic acids, and amino acids. The TSS content reflects the degree of starch hydrolysis into sugars, which is an indicator closely related to sweetness[22]. In general, the TSS of all groups gradually increased with storage time (Figure 6 and **Table 3**). The uncoated sample exhibited a rapid increase in TSS, reaching 25.67% on day 5, while the CH-sCeO_2-coated sample only reached 23.70% on day 8. This demonstrates the effectiveness of the CH-sCeO_2 coating in slowing the conversion of starch into sugars compared to the control group. As shown in previous sections, the delayed respiration peak in coated fruits results in the delayed synthesis and utilization of metabolites, leading to lower TSS due to the slower hydrolysis of carbohydrates into sugars.

TA gradually decreased over time as organic acids were consumed during respiration [18]. In general, the TA of all groups decreased with storage time (Figure 7 and Table 3). The control sample and the Kadozan-coated sample exhibited a more rapid decrease in TA compared to the other groups, while the CH-sCeO_2-coated group exhibited the slowest decline in TA. The control sample decreased from 5.03 (day 0) to 2.12 (day 5), while the CH-sCeO_2 sample had a TA of 2.23 on day 8, highlighting the effectiveness of the CH-sCeO_2 coating at delaying acidity loss during storage. This highlights the role that CeO_2 may play in inhibiting oxidation reactions and the adsorption of ethylene, thus slowing down the physiological ripening process of the fruit. Conse-

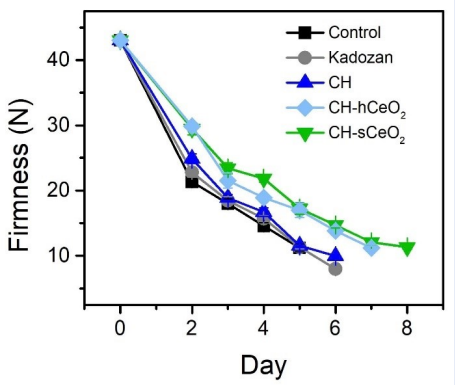

Figure 5: Firmness of bananas across eight days of storage.

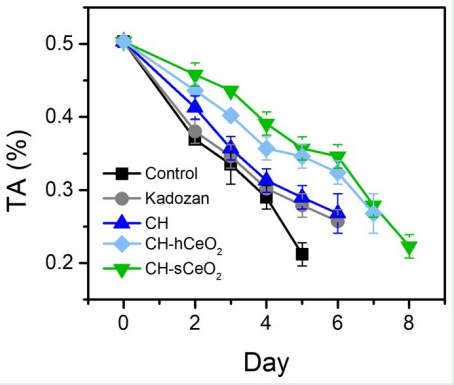

Figure 7: Titratable acidity across eight days of storage.

quently, the application of a nanocomposite coating helps maintain freshness and nutritional value during storage.

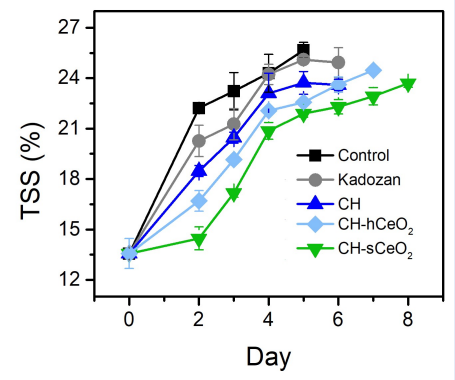

Figure 6: Total soluble solids content across eight days of storage.

Changes in pH are associated with what is potentially the most critical phase of banana ripening: the rapid consumption of substrates and metabolites as energy sources or organic acid metabolism[21]. Figure 8 and Table 3 illustrate the gradual increase in pH throughout the storage period due to the progressive consumption of organic acids during ripening. The control group exhibited a more rapid increase in pH compared to the other treatments, reaching a pH of 5.39 by day 5, while the CH-sCeO$_2$-coated samples exhibited the slowest pH rise, reaching a pH of 5.46 on day 8. Effective pH regulation reflects greater internal stability and chemical integrity during storage[22]. This is consistent with previous investigations into pH increases during banana storage[4,23] . In summary, bananas coated with CH-sCeO$_2$ exhibited the slowest

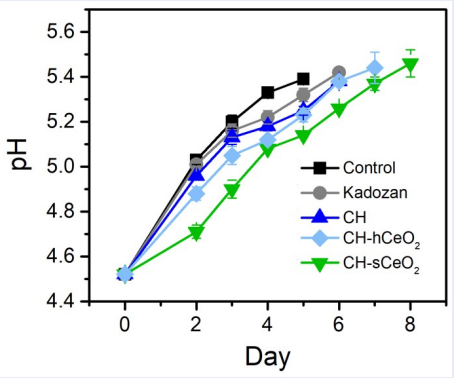

Figure 8: pH of bananas across eight days of storage.

respiration rate and metabolic activity, thus delaying ripening and extending the post-harvest shelf life of the fruit.

^{abcdefg}Different letters within the same column indicate statistically significant differences across different days of storage according to the Tukey HSD test ($p < 0.05$).

^{1234} Different numbers within the same row indicate statistically significant differences across different coatings during storage according to the Tukey HSD test ($p < 0.05$).

Table 4 shows that using the dip-coating technique for CH-hCeO$_2$ and CH-sCeO$_2$ extends banana shelf life to around ~10–12 days; in contrast, the spray-coating technique extends shelf life by 7–8 days. Immersion allows the solution to reach all fruit surfaces, including depressions and microcracks that sprays may miss, leading to a more continuous and uniform film layer. In addition, the dip-coating enhances polymer

Table 3: Changes in total soluble solids, total acidity, and pH of bananas across 8 days of storage.

		Control	Kadozan	CH	CH-hCeO_2	CH-sCeO_2
Total soluble solids content (%)	Day 0	$13.57^{a,1}\pm0.90$	$13.57^{a,1}\pm0.90$	$13.57^{a,2}\pm0.90$	$13.57^{a,2}\pm0.90$	$13.57^{a,3}\pm0.90$
	Day 2	$22.23^{b,1}\pm0.21$	$21.27^{b,1}\pm0.93$	$20.47^{b,2}\pm0.33$	$16.70^{b,2}\pm0.62$	$14.47^{b,3}\pm0.68$
	Day 3	$23.23^{b,1}\pm1.11$	$21.27^{b,1}\pm0.93$	$20.47^{b,2}\pm0.33$	$19.17^{b,2}\pm0.09$	$17.17^{b,3}\pm0.25$
	Day 4	$24.30^{c,1}\pm1.12$	$24.23^{c,1}\pm0.60$	$23.10^{c,2}\pm1.20$	$22.07^{c,2}\pm0.17$	$20.87^{c,3}\pm0.50$
	Day 5	$25.67^{cd,1}\pm0.47$	$25.10^{cd,1}\pm0.08$	$23.73^{cd,2}\pm0.68$	$22.57^{cd,2}\pm0.17$	$21.90^{cd,3}\pm0.22$
	Day 6	-	$24.93^{d,1}\pm0.90$	$23.60^{d,2}\pm0.33$	$23.63^{d,2}\pm0.45$	$22.30^{d,3}\pm0.43$
	Day 7	-	-	-	$24.47^{d,2}\pm0.05$	$22.93^{d,3}\pm0.52$
	Day 8	-	-	-	-	$23.70^{d,3}\pm0.24$
Total acidity (10-1 %)	Day 0	$5.03^{a,1}\pm0.00$	$5.03^{a,12}\pm0.00$	$5.03^{a,2}\pm0.00$	$5.03^{a,3}\pm0.00$	$5.03^{a,3}\pm0.00$
	Day 2	$3.69^{b,1}\pm0.00$	$3.80^{b,12}\pm0.16$	$4.13^{b,2}\pm0.16$	$4.36^{b,3}\pm0.00$	$4.58^{b,3}\pm0.16$
	Day 3	$3.35^{c,1}\pm0.27$	$3.46^{c,12}\pm0.16$	$3.57^{c,2}\pm0.16$	$4.02^{c,3}\pm0.00$	$4.36^{c,3}\pm0.00$
	Day 4	$2.90^{d,1}\pm0.16$	$3.02^{d,12}\pm0.00$	$3.13^{d,2}\pm0.16$	$3.57^{d,3}\pm0.16$	$3.91^{d,3}\pm0.16$
	Day 5	$2.12^{e,1}\pm0.16$	$2.79^{e,12}\pm0.16$	$2.90^{e,2}\pm0.16$	$3.46^{e,3}\pm0.16$	$3.57^{e,3}\pm0.16$
	Day 6	-	$2.57^{e,12}\pm0.16$	$2.68^{e,2}\pm0.27$	$3.24^{e,3}\pm0.16$	$3.46^{e,3}\pm0.16$
	Day 7	-	-	-	$2.68^{f,3}\pm0.27$	$2.79^{f,3}\pm0.16$
	Day 8	-	-	-	-	$2.23^{f,3}\pm0.16$
pH	Day 0	$4.52^{a,1}\pm0.02$	$4.52^{a,12}\pm0.02$	$4.52^{a,23}\pm0.02$	$4.52^{a,4}\pm0.02$	$4.52^{a,3}\pm0.02$
	Day 2	$5.03^{b,1}\pm0.02$	$5.01^{b,12}\pm0.01$	$4.96^{b,23}\pm0.00$	$4.88^{b,4}\pm0.03$	$4.71^{b,3}\pm0.03$
	Day 3	$5.20^{c,1}\pm0.03$	$5.16^{c,12}\pm0.03$	$5.13^{c,23}\pm0.03$	$5.05^{c,4}\pm0.04$	$4.90^{c,3}\pm0.04$
	Day 4	$5.33^{d,1}\pm0.02$	$5.22^{d,12}\pm0.03$	$5.18^{d,23}\pm0.02$	$5.12^{d,4}\pm0.01$	$5.08^{d,3}\pm0.00$
	Day 5	$5.39^{e,1}\pm0.01$	$5.32^{e,12}\pm0.03$	$5.25^{e,23}\pm0.02$	$5.23^{e,4}\pm0.03$	$5.14^{e,3}\pm0.01$
	Day 6	-	$5.42^{f,12}\pm0.02$	$5.38^{f,23}\pm0.02$	$5.38^{f,4}\pm0.02$	$5.26^{f,3}\pm0.01$
	Day 7	-	-	-	$5.44^{g,4}\pm0.07$	$5.37^{g,3}\pm0.03$
	Day 8	-	-	-	-	$5.46^{g,3}\pm0.06$

penetration and adhesion, improving the mechanical integrity and barrier properties of the coating. In contrast, spray-coating uses less solution and reduces the risk of microbial cross-contamination.

CONCLUSIONS

The results of this study show that a chitosan spray integrated with sCeO_2 nanoparticles is highly effective at preserving post-harvested bananas. This nanocomposite coating slows browning, respiration, softening, and weight loss, while also reducing physicochemical changes (i.e., TSS, TA, and pH) throughout the storage. The CH-sCeO_2 coating exhibited the best performance out of all samples tested, which included uncoated samples and samples with pure chitosan coating, commercial coating (Kadozan), and CH-hCeO_2 coating, highlighting its strong practical potential for banana preservation. This study contributes to the literature by providing an alternative to traditional preservatives in the form of an effective, safe, and feasible approach to post-harvest preservation.

LIST OF ABBREVIATIONS

TSS : Total soluble solids

TA : Total acidity

CONFLICTS OF INTEREST

We declare that there are no conflicts of interest among the members of the research team.

Table 4: Comparison of the effectiveness of chitosan-based nanocomposite coatings for enhancing the storability of post-harvest bananas.

Coating formulation	Banana harvesting location	Coating method	Storage condition	Weight loss	Ref
Chitosan and 3% (w/w) silver-immobilized graphene oxide	Ho Chi Minh City, Viet Nam (Musa acuminata 'cau')	Dipping	10 days at room temperature	14%	22
Chitosan/gum arabic/0.5% (w/w) ZnO NPs (pretreated with 0.01% NaClO)	Ho Chi Minh City, Viet Nam (Musa acuminata L.)	Dipping	17 days at 35°C and 54 % RH	~15.5%	24
Chitosan with 1.5% (w/w) $sCeO_2$	Lam Dong province, Viet Nam (Musa sapientum L. 'Laba')	Dipping	10 days at 20°C and 64% RH	15.25%	16
Chitosan with 1.5% (w/w) $hCeO_2$	Lam Dong province, Viet Nam (Musa sapientum L. 'Laba')	Dipping	12 days at 20°C and 64% RH	16.32%	15
Chitosan with 1.5% (w/w) $sCeO_2$	Lam Dong province, Viet Nam (Musa sapientum L. 'Laba')	Spraying	8 days at 20°C and 64% RH	16.27%	This study
Chitosan with 1.5% (w/w) $hCeO_2$	Lam Dong province, Viet Nam (Musa sapientum L. 'Laba')	Spraying	7 days at 20°C and 64% RH	14.37%	This study

AUTHORS' CONTRIBUTIONS

Thien Dinh Le: Conducted experiments, performed statistical analysis, compiled measurement data, and drafted the manuscript.

Bao-Tran Tran Pham: Conducted experiments and performed sample measurements.

Thuong Thi Nguyen: Provided research direction, advised on the research approach, and revised the manuscript.

Ha Thuc Chi Nhan: Provided research direction, advised on the research approach, and revised the manuscript.

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