Eco-Friendly Calcium Nanoparticle Coatings: A Sustainable Strategy for Postharvest Preservation of Food Crops

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ABSTRACT

Tomato spoilage remains a major postharvest challenge in Nigeria, where poor preservation methods cause 40–50% annual yield losses. This study explored the use of eco-friendly calcium nanoparticles (CaNPs) synthesized from orange peel extract (OPE) as a sustainable coating to extend tomato shelf life. OPE was prepared by aqueous extraction at 60 °C for 1 hour and reacted with 1 mM calcium nitrate ($Ca(NO_3)2$) to produce CaNPs via green synthesis. Colour transition from light to deep golden brown was observed, with UV–Visible spectroscopy showing maximum absorbance at 326 nm and TEM revealing spherical nanoparticles and particle size (72.35–93.34 nm). Fresh tomatoes coated with 0.5 mM and 0.8 mM CaNPs were stored for 28 days at ambient temperature and compared with uncoated controls. Coated fruits retained higher moisture (84.01–84.22%) and showed enhanced crude protein, fat, fibre, and carbohydrate contents. Colour analysis (L*, a*, b*) indicated better retention of brightness, redness, and yellowness. CaNPs coatings effectively preserved nutritional and sensory qualities, reducing water loss and pigment degradation. Using orange peel as a reducing agent valorises agricultural waste and promotes green nanotechnology as a low-cost, biodegradable strategy for reducing postharvest losses and improving food security in developing nation's economies.

INTRODUCTION

The postharvest process encompasses all stages from harvesting to consumption, including handling, storage, packaging, transportation, and marketing (Kader, 2025). This stage is critical for perishable crops like tomatoes due to their potentials for high spoilage, mechanical damage, and nutrient loss (Kader, 2025). Food crops play a major role in human nutrition, especially as sources of phytonutrients, vitamins (A, C, and K), minerals, dietary fibres, and phytochemicals for overall good health (Devidutta et al., 2021). Also, vegetables play an important role in food and nutrition security (Amaechi et al., 2021). Levels of antioxidants in plants can vary with genotype, stage of maturity, plant part consumed, and conditions during growth and postharvest handling (Creola et al., 2022). Phytochemicals in vegetables reduce the risk of chronic disease, protect against free-radical damage, modify metabolic activation, and detoxify carcinogens by influencing processes that alter the course of tumour cells (Craig and Beek, 2018).

Consuming tomatoes is believed to be effective for diarrhoea, asthma, toothache, colds, fever, sore throat, hangover, and stabilizing blood pressure. It is generally used as a spice in medicine, as well as being a natural colorant in many types of foods (Amaechi et al., 2021). Tomatoes are highly perishable and prone to rapid postharvest deterioration due to their high moisture content, soft texture, and sensitivity to microbial spoilage, these makes their transportation and storage challenging (Nwachukwu et al., 2023). Mechanical damage during handling, water loss, and rapid ripening further reduce shelf life and market quality. These factors often result in economic losses, especially in regions lacking proper cold storage or preservation technologies. According to Nwachukwu et al.(2023), over 40% of harvested tomatoes in parts of Nigeria are lost postharvest due to poor handling practices, temperature fluctuations, and microbial decay during transportation and storage (Nwachukwu et al., 2023).

Several methods are currently used for the preservation of tomatoes, including refrigeration, canning,drying, chemical treatments, and more recently, edible coatings and nanotechnology-based approaches. While refrigeration slows down microbial growth and respiration; it can cause chilling injuries and it is energy-intensive. Canning and drying extend shelf life but often leads to loss of nutrient and sensory quality. The use of chemical preservatives is highly regulated due to potential toxicity concerns. However, edible coatings and nanoparticle-based methods are promising techniquessince studies have shown that they reduce spoilage while maintaining quality; however, their scalability, cost, and consumer acceptance remain challenges. According to Azeez *et al.* (2023), despite advances in postharvest technologies, a lack of infrastructure and standardized practices still limits the widespread adoption of these methods in many developing countries. This study therefore seeks to reinforce the applications of greenly synthesized nanoparticles, in this case calcium nanoparticles for developing biodegradable coatings (Dias, 2016) which can be appliedto preserve the quality and shelf life of tomatoes. The main objectives of this study are to biosynthesize calcium nanoparticles (CaNPs) and characterize the biosynthesized CaNPs using spectrophotometric and microscopic methods/techniques (UV-Vis and TEM), and to apply the CaNPs as coating for tomatoes, and evaluate the effects of the coating on the storability attributes of tomatoes through the proximate analysis.

METHODOLOGY

Materials

Calcium Nitrate (Ca(NO3)2was obtained from the Industrial Microbiology and Nanobiotechnology laboratory,Ladoke Akintola University of Technology Ogbomoso.Orange wasprocured from a local market,oja waso, Ogbomoso (8.1657° N, 4.2575° E), and freshly harvested tomatoes (Solanum lycopersicum)were procured from local farm Pakiotan Ogbomoso,Nigeria (8.1753° N, 4.2447° E).

Methods

Collection and Processing of Orange Peels

Matured orange were procured from local market, oja waso tun tun, inOgbomoso, Nigeria. The oranges were peeled, and the peels were dried at 40°C in the laboratory. The dried peels were blended and sieved (0.5mm mesh) to obtain fine orange peel powder used in the study.

Extraction from Orange Peel

Approximately 1g of dried powdered orange peel was dissolved in 100ml of distilled water. This was incubated in water bath at 60°Cfor 1 h. The mixture was thereafter centrifuged at 4000 revolution per minute (rpm) for 20 min and the supernatant obtained was used as the orange peel extract for the biosynthesis of CaNPs biosynthesis.

Biosynthesisof CaNPs

About 5 ml of either 0.5 mM or 0.8 mM Calcium nitrate solution was reacted with 1 ml of orange peel extract. The mixture was incubated inside water bath at 60 °C for 1 h after which development of colour was monitored to confirm the biosynthesis of the nanoparticles.

Characterization of Biosynthesized CaNPs

The maximum wavelengths of absorption of CaNPs due to the surface plasmon resonance of the nanoparticles were determined by scanning from 200 to 500 nm using UV–Vis spectrophotometer. Also, the shapes and sizes of the CaNPs were determined usingthe Transmission Electron Microscopy (TEM).

Sample Preparation of Tomato Coated Green-Synthesized CaNPs

The orange peel extract (OPE) concentration is first varied (0.2ml, 0.4ml, 0.5ml, 0.6ml, 0.8ml, 1ml) to know the best concentration for (CaNO3)2 synthesized. The best concentration was 0.5mM and 0.8mM. Followed by variation of soaking period (30 seconds, 1 minute, and 2 minutes), to know the best duration of introducing the CaNPs to the tomato and the best result of soaking time is 1minute. For 0.5mM, 0.8mM, and Untreated were stored for 28 days which is picked in 2 days interval for analysis (Day 0, Day 2, Day 4, Day 6, Day 8, Day 10, Day 12, Day 14, Day 16, Day 18, Day 20, Day 22, Day 24, Day 26, Day 28) (Day 0 – Day 28), Day 0 to Day 6 is week 1, Day 8 – Day 14 is week 2, Day 16 – Day 20 is week 3, Day 22 – Day 28 is Week 4, and Week 0 is tomatoes before coating (Naito et al., 2024).

Application of Green Synthesized CaNPs Coating on Tomato

The procured tomatoes were washed with distilled water for few min to remove soil debris and unwanted materials, then allowed to dry at room temperature. The tomatoeswere weighed using weighing balance (SF - 400),after which tags were used to indicate the weights of each tomato. Each tomato was coated with CaNPs using immersion technique that involve immersing the tomato for about 1 min in the CaNPs contained in a beaker, then removed and placed in a sieve in order to drain and dry. Each tomato was then wrapped with an aluminium foil and kept at ambient temperature for 28 days (Naito *et al.*, 2024). Fresh tomatoes not immersed in CaNPs were kept as control which is also regarded as the uncoated tomatoes. Observations at 7 days interval and recorded for both the coated and uncoated tomatoes.

Proximate Analysis

Determination of Moisture Content

Moisture content of the coated and uncoated tomatoes was evaluated using a 202-1B drying oven at 105 °C for 1 h. About 2 g sample was used in carrying out the moisture analysis (Wei and Xin, 2016).The moisture content can be calculated according to equation 1 (Gyamfi, 2024).

$$\%\ \text{Moisture content} = \frac{weight\ loss\ of\ sample}{weight\ of\ the\ original\ sample} \text{ x } 100 \quad (1)$$

Determination of Ash Content

The crude ash content of the coated and uncoated tomatoes was determined using the method described by AOAC (2016). About 5 g of the sample was analysed using the inorganic residue remaining after the water and organic matter have been removed from the sample by heating in a muffle furnace at a temperature of 500 – 600 °C. The ash content was calculated using equation 2 (Gyamfi, 2024).

$$\%\ \text{Ash content} = \frac{weight\ of\ ash}{weight\ of\ the\ original\ sample} \text{ x } 100 \quad (2)$$

Determination of Fat Content

The fat content of the sample was evaluated using the Soxhlet extraction technique described by AOAC (2016). About 15 g of the sample was weighedin a fat-free thimble, then the lipids were extracted with a non-polar solvent (petroleum ether), followed by gravimetric measurement (AOAC 2016). The fat content was calculated using equation 3 (Gyamfi, 2024).

$$\%\ \text{Crude fat content} = \frac{Extracted\ fat\ of\ sample}{\text{weight of sample}} \text{ x } 100 \quad (3)$$

Determination of Crude Protein

The Crude Protein content of the tomato samples was evaluated using the Kjeldahl technique (Gyamfi, 2024). A ground sample (5 g) was weighed in a Kjeldahl digestion tube, and 2 Kjeltab CT 3.5 (7 g K_2SO_4 + 0.210 g $CuSO_4$ x $5H_2O$ + 0.210 g TiO_2) was added, followed by 15 ml of concentrated H_2SO_4, this was heated for 60 min, then cooled 15 for min, after which distillation was carried out, the crude protein value was calculated automatically using the kjeldahl technique (AOAC 2016).

Determination of Crude Fibre

Crude fibre content of the tomato samples was evaluated using the Fibertec^{TM} 8000 auto-fibre analysis system. Both coated and uncoated samples were analysed using the AOAC 978.10 method. The process involved acid and alkaline digestion, filtration, drying, incineration, and weighing of the residue to estimate the fibre content gravimetrically (AOAC 2016). The crude fibrewas calculated using equation 4, (Gyamfi, 2024).

$$\%\text{Crude fibre content} = \frac{W2-(W3+C)}{W2} \times 100 \quad (4)$$

W_2 = weight of crucible and dried residue before ashing

W_3 = weight of crucible and ash after incineration

C = weight of sample taken for analysis

Determination of Carbohydrate Content

Carbohydrate content of the tomato samples was evaluated using the difference in means of 100 % of other proximate chemical compositions using formula 5 (AOAC 2016).

% Carbohydrate content = 100 - (% crude protein + % fat + % ash + % moisture content + % fibre) (5)

Determination of Colour

The colour of the tomato samples was determined using a colorimeter device (WR10QC). The colour was determined by cutting through vertically so that the surface of the tomatowill be accessible for the light ray coming from the colorimeter(Kahramanoglu *et al.,* 2018).

Statistical Analysis

Statistical analysis was evaluated using Statistical Package for Social Sciences (SPSS) version 20; combinations of analytical techniques were employed for data analysis to achieve the objectives of this study. This includes Analysis of Variance (ANOVA) at $p \leq 0.05$.

RESULTS AND DISCUSSION

Biosynthesis and Characterization of Calcium Nanoparticles (CaNPs)

The biosynthesis of the CaNPs was confirmed by the colour change of the colloidal solution from light golden brown to deeper golden brown which was observed in both 0.5 and 0.8 mM solution. This result is similar to the report by Krishna *et al.,* (2023).The results obtained from UV–Vis spectra for CaNPs (Figure 1) revealed maximum absorbance at region of 326nm for both 0.5 and 0.8mMsolution. The size and surface morphology of the biosynthesized CaNPs were studied using TEM analysis. The TEM image (Figure 2) showed the CaNPs at a 100nm scale. It was revealed that thecalcium nanoparticles were a spherical in shapeswith sizes that rangedfrom 72.35 to 93.34 nm. According to the report of Zhao *et al.* (2022), CaNPs with sizes of 94.4 nm and 93.3 nm were reported synthesized.

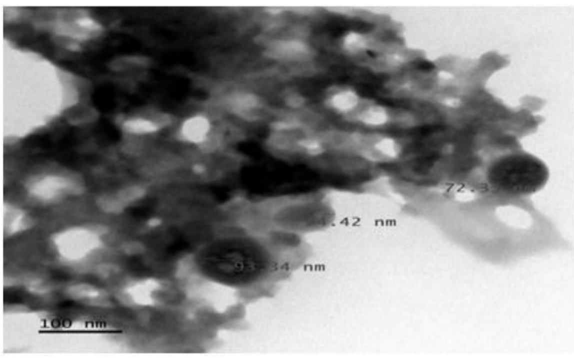

Figure 1:TEM Image of Calcium Nanoparticles at 100 nm Scale

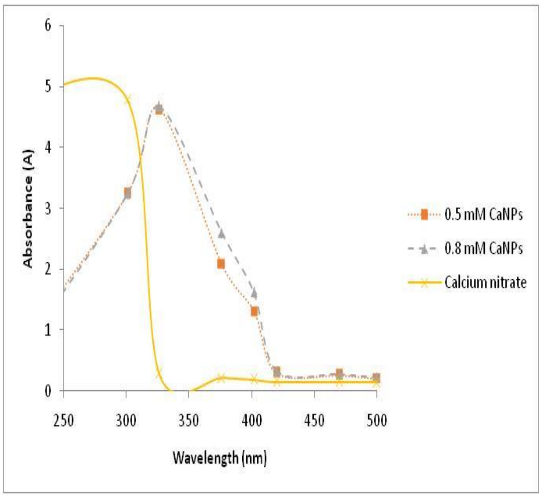

Figure 2. UV-Vis Spectra of Biosynthesized CaNPs and Calcium Nitrate Solution

Proximate Composition of the CaNPs-coated and Uncoated Tomatoes

The proximate analysis of uncoated and CaNPs-coated tomatoes is presented in Table 1. The moisture content of the samples coated with 0.5 mM (84.01 ± 0.10%) and 0.8 mM CaNPs (84.22 ± 0.99%) were higher than that of the uncoated tomato (81.40 ± 0.44%). The observed increase indicates that the CaNPs coating reduced water loss during storage by forming a semi-permeable barrier that minimized transpiration and respiration rates (Siddiqui *et al.*, 2021). The water loss prevention capacity slightly increased as the nanoparticle concentration increased. Moisture content is a critical parameter in evaluating the effectiveness of nanoparticle coatings in food preservation. It helps assess how well the coating prevents water loss, which directly impact the texture, weight, and shelf life of perishable crops (Siddiqui *et al*., 2021). It was also observed that the CaNPs coating impacted positively on the crude protein of the tomatoes. The result obtained showed that the crude protein content of the 0.5 mM CaNPs-coated tomato (3.03 ± 0.01%) and 0.8 mM CaNPs-coated tomato (3.24 ± 0.13%) were significantly higher than the uncoated sample (2.93 ± 0.05%). The increase was also progressive with increased concentration of nanoparticles. This suggests that the coating helped maintain the nitrogenous components of the fruit, possibly by reducing enzymatic degradation and proteolysis (Magri *et al*., 2024).

Similarly, crude fat content increased in the coated samples compared with the uncoated with the 0.8 mM CaNPs-coated tomato (2.78 ± 0.06%) showing the highest fat content. These results reflect a reduction in lipid oxidation and better membrane stability in coated fruits (Ji *et al*., 2022). Fat content analysis measures the total lipid content in food, which is important for monitoring quality changes during storage, and whether nano-coatings affect lipid oxidation, migration, or degradation (Zahran *et al*., 2020).

The results obtained for both the crude fibre and ash contents also reflect the same trend with increase revealed with the coated samples compared with the uncoated sample. In both analyses, the 0.8 mM CaNPs-coated tomato exhibited the highest result having 1.97 ± 0.08% for crude fibre and 0.51 ± 0.01% for the ash content higher than 1.70 ± 0.04% and 0.42 ± 0.03% , in the uncoated for crude fibre and ash contents, respectively. Crude fibre analysis measures the indigestible portion of plant foods, mainly cellulose and lignin, which is important for assessing textural and nutritional changes (Kahranmanoglu *et al*., 2018). Also, Ash content analysis determines the total mineral residue left after the complete combustion of organic matter in a food sample, it helps assess whether coating materials influence the mineral composition (Al-Naamani *et al*., 2016).The increase in ash content may be attributed to the mineral enrichment effect of the calcium nanoparticles, which can contribute additional mineral ions during coating. The carbohydrate content results also indicated that the CaNPs coated tomatoes showed notable increase compared with the uncoated tomatoes.

Table 1: Proximate Composition of Coated and Uncoated Tomato

Sample	Moisture (%)	Crude protein (%)	Crude fat (%)	Crude fibre (%)	Ash (%)	CHO(%)
A	81.40 ± 0.44[a]	2.93 ± 0.05[a]	2.46 ± 0.02[a]	1.70 ± 0.04[a]	0.42 ± 0.03[a]	7.32 ± 0.87[a]
B	84.01 ± 0.10[a]	3.03 ± 0.01[a]	2.63 ± 0.05[a]	1.84 ± 0.05[a]	0.50 ± 0.02[a]	8.09 ± 0.16[a]
C	84.22 ± 0.99[a]	3.24 ± 0.13[a]	2.78 ± 0.06[b]	1.97 ± 0.08[a]	0.51 ± 0.01[a]	11.01 ± 0.49[a]

Values are expressed as Mean ± SD of triplicate readings. Mean values along the same column with different superscripts are significantly different ($p \leq 0.05$).

Where A, B and C represent uncoated tomato, tomato coated with 0.5 mM CaNPs, and tomato coated with 0.8 mM CaNPs, respectively.

The 0.8 mM CaNPs-coated tomato exhibited the highest carbohydrate content having 11.01 ± 0.49% while the uncoated tomato (7.32 ± 0.87%) showed the least carbohydrate content. This could be linked to a slower rate of respiration and sugar metabolism during storage, resulting in better retention of carbohydrates (Shiekh *et al*., 2021). Carbohydrate content analysis helps determine the nutritional and energy value of food products, especially during storage and preservation. This analysis also assesses the impact of the coating on the sugar degradation or retention (Ali *et al*., 2019). Overall, the results indicate that CaNPs coatings enhanced the proximate composition and nutritional stability of tomatoes. The effect was more pronounced at the higher CaNPs concentration (0.8 mM), which suggests improved preservation of biochemical components and reduced deterioration during storage.

Effects of CaNPs-Coating on Stored Tomatoes

Table 2 shows the colour parameters of coated and uncoated tomatoes over 28 days of storage. The lightness (L) values increased slightly with time in all samples, although coated tomatoes generally maintained higher or comparable brightness levels than the uncoated control. By day 28, tomatoes coated with 0.5 mM CaNPs had the highest L value (17.23 ± 4.48) compared with 10.52 ± 0.35 in uncoated tomatoes, indicating that the coatings helped delay surface darkening and senescence (Saleem *et al*., 2023) and also prevents enzymatic browning, pigment degradation (Kahramanoglu *et al*., 2018).

The redness (a) values, which correspond to lycopene accumulation, increased in all samples during storage, consistent with progressive ripening. However, coated tomatoes, particularly those treated with 0.8 mM CaNPs showed significantly higher redness values at later stages with the highest recorded on day 21 (20.08±5.16). On day 28, the redness values of 16.65–17.70 were observed for coated samples, whereas uncoated tomatoes recorded only 7.90. This implies the possible impacts of the CaNPs coatings in the maintenance of colour intensity and reduced degradation of lycopene pigments.

Similarly, the yellowness (b) values were generally higher in coated tomatoes than in uncoated ones, particularly towards the end of storage. On day 28, the 0.5 mM CaNPs-coated sample recorded the highest yellowness value (38.98 ± 7.86), compared to 7.01 ± 1.35 in the uncoated sample. The higher yellowness values suggest better retention of carotenoid pigments, possibly due to the barrier effect of the coating against oxygen diffusion (Ruiz

Medina *et al*., 2025). The comparism of colour analysis result with previous work done on colour analysis result is shown in Table 3.

Table 2: Colour Measurements of the CaNPs-coatedand Uncoated Tomatoes

Colour	0.5 mM	0.8 mM	Untreated
		WEEK0	
L*	12.88 ± 0.48	12.80 ± 1.79	13.06 ± 1.98
a*	$6.31\pm0.91^{a,b}$	8.33 ± 1.07^{b}	6.20 ± 0.94^{a}
b*	14.29 ± 7.07	8.82 ± 4.63	9.58 ± 5.77
		WEEK1	
L*	17.09 ± 2.92^{b}	13.13 ± 1.01^{a}	11.13 ± 0.54^{a}
a*	10.41 ± 1.61^{b}	11.03 ± 0.52^{b}	8.13 ± 0.36^{a}
b*	11.49 ± 5.46^{a}	10.05 ± 4.25^{a}	3.25 ± 0.45^{a}
		WEEK2	
L*	15.29 ± 1.55	14.19 ± 0.72	14.09 ± 5.30
a*	10.71 ± 3.43	12.99 ± 2.44	10.35 ± 2.60
b*	25.57 ± 18.70	17.57 ± 9.64	23.07 ± 13.70
		WEEK 3	
L*	16.57 ± 0.64	16.99 ± 2.19	16.02 ± 4.49
a*	18.92 ± 5.12^{b}	20.08 ± 5.16^{b}	8.28 ± 3.63^{a}
b*	32.73 ± 18.62	46.54 ± 13.32	22.29 ± 12.94
		WEEK 4	
L*	17.23 ± 4.48^{b}	$14.72\pm0.74^{a,b}$	10.52 ± 0.35^{a}
a*	17.70 ± 2.59^{b}	16.65 ± 1.82^{b}	7.90 ± 1.40^{a}
b*	38.98 ± 7.86^{b}	24.94 ± 10.47^{b}	7.01 ± 1.35^{a}

Values are expressed as Mean ± SD of triplicate readings. Mean values along the same column with different superscripts are significantly different ($p\leq0.05$).

Where L*, a* and b* represent lightness orlight vs. dark, redness or red vs. green, and yellowness or yellow vs. blue, respectively.

Table 3: Comparism of Result with Previous Work Done on the Preservation of Fruits

Author	Nanoparticle used	Fruit preserved	Deduction
This study	CaNP	Tomato	The shelf life of tomato was extended for 28 day when compared to uncoated fruit. It prevent enzymatic browning and decay
Khare et al. (2024)	ZnO and TiO2 Nanoparticles	Guava fruit	It prevent microbial activity and oxidative stress
Veeramani et al. (2024)	CaO NP	blueberries and blackberries,	It extends fruits shelf life for 20-day when compared to control (untreated) fruits.
Ding et al. (2024)	Silver Nanocomposites	Tomato	It inhibit the growth of fungus and increased tomato shelf life to 17 days.

Jacuinde-Guzman et al. (2024)	CaO NP	fresh-cut seedless watermelon	Shelf life was extended when compared to control
Ali (*et al.*, 2019)	ZnONP	Tomato	It preserves colour better when compared with the control

The highlights of the promising and diverse applications of syntesized nanoparticles in post-harvest fruits preservation was presented in Table 3. The studies presented by Khare et al. (2024) and Ding et al. (2024) demonstrate the dual functionality of metal-based nanoparticles, with zinc oxide/titanium dioxide targeting microbial activity and oxidative stress in guava, and silver nanocomposites effectively inhibiting fungal growth in tomatoes while extending shelf life. In Similarly, it was reported in the findings of Veeramani et al. (2024) where calcium oxide nanoparticles shows a significant practical outcome, successfully preserving blueberries and blackberries for an extended 20-day period. This collective evidence underscores nanoparticles' potential as a potent tool against the primary causes of post-harvest spoilage. These published results, including the investigation into fresh-cut watermelon by Jacqueline-Guzman et al. (2024), are highly encouraging for the field of the application of nanoparticle in post-harvest preservation. They not only validate the efficacy of different nanoparticle compositions across a variety of fruit types from whole berries and tomatoes to delicate fresh-cut produce, but also pave the way for optimizing specific formulations for targeted applications. The consistent positive findings across these recent studies strongly advocate for continued and expanded research in this area, aiming to develop safe, efficient, and commercially viable nano-enabled coatings to reduce food waste and enhance global food security.

CONCLUSION

This study successfully demonstrated the potential of green-synthesized calcium nanoparticles (CaNPs) derived from orange peel extract as an effective, eco-friendly coating for extending the shelf life and maintaining the nutritional quality of fresh tomatoes. The CaNPs exhibited desirable physicochemical characteristics, such as spherical shape and nanoscalesize, which enhanced their interaction with the fruit surface, forming a semi-permeable layer that minimized moisture loss, delayed ripening, and reduced biochemical deterioration. Tomatoes coated with 0.8 mM CaNPs retained superior moisture, protein, fat, and carbohydrate contents and exhibited better colour stability compared with uncoated controls. Beyond improving storability for up to 28 days, this approach also provides a sustainable means of transforming agricultural waste into value-added nanomaterials. The findings point out the promise of green nanotechnology as a low-cost and biodegradable strategy for postharvest preservation, particularly in regions lacking cold-chain infrastructure. Integrating such innovations into local food systems can significantly reduce tomato spoilage, enhance food security, and promote environmental sustainability.

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