



OPEN ACCESS

EDITED BY

Guadalupe Virginia Nevárez-Moorillón,
Autonomous University of Chihuahua, Mexico

REVIEWED BY

Chigozie Charity Okwuwa,
Universiti Malaysia Pahang, Malaysia
Condro Wibowo,
Jenderal Soedirman University, Indonesia

*CORRESPONDENCE

Devanushi Dutta

✉ devanushid@yahoo.com

RECEIVED 24 September 2025

REVISED 10 January 2026

ACCEPTED 19 January 2026

PUBLISHED 01 April 2026

CITATION

Dutta D and Dutta P (2026) Efficiency of
gluconate-stabilized silver nanocoating for
shelf-life enhancement of *Khasi* mandarin
(*Citrus reticulata*, Blanco).

Front. Sustain. Food Syst. 10:1711722.

doi: 10.3389/fsufs.2026.1711722

COPYRIGHT

© 2026 Dutta and Dutta. This is an
open-access article distributed under the
terms of the [Creative Commons Attribution
License \(CC BY\)](#). The use, distribution or
reproduction in other forums is permitted,
provided the original author(s) and the
copyright owner(s) are credited and that the
original publication in this journal is cited, in
accordance with accepted academic
practice. No use, distribution or reproduction
is permitted which does not comply with
these terms.

Efficiency of gluconate-stabilized silver nanocoating for shelf-life enhancement of *Khasi* mandarin (*Citrus reticulata*, Blanco)

Devanushi Dutta^{1*} and Pranab Dutta²

¹College of Post Graduate Studies in Agricultural Sciences, CAU (Imphal), Umiam, Meghalaya, India,

²College of Agriculture, Kyrdenkulai, CAU (Imphal), Umiam, Meghalaya, India

Khasi mandarin (*Citrus reticulata*, Blanco) is a widely cultivated commercial fruit crop in Meghalaya, India. The present research aims to assess the potential for synthesizing and characterizing gluconate-stabilized silver nanoparticles (Glu-Ag NPs) to enhance the shelf-life of *Khasi* mandarin by inhibiting *Penicillium italicum*. Glu-Ag NPs showed the highest (58.23%) mycelial growth inhibition at 250 ppm. The lowest diseases severity index (DSI) of 13.9% was recorded in *Khasi* mandarins that were nanocoated for 120 s, followed by wax-coated mandarins (30.5%). The highest DSI (66.7%) was recorded in uncoated mandarins. On studying different biochemical parameters of the juice extracted from treated and untreated mandarins, the highest titratable acidity (0.061 g/100 g) was found in the juice extracted from uncoated mandarins. Similarly, the highest browning index (0.975) was recorded in the juice stored at ambient conditions (22 ± 2 °C) compared to the juice stored under refrigerated conditions (4 °C) (0.476). Nanocoated mandarins exhibited the lowest fruit weight loss at 3.008%. Thus, the antimicrobial activity of Glu-Ag NPs and their coating properties significantly enhance the shelf life of *Khasi* mandarin by reducing the DSI.

KEYWORDS

gluconate, *Khasi* mandarin, *Penicillium italicum*, shelf life, silver nanoparticle

1 Introduction

A major concern in the agricultural system is post-harvest degradation, which converts fresh harvests into products that are unfit for human consumption. Different biotic and abiotic factors contribute to post-harvest losses. Microbes such as bacteria, yeast, and molds are the major biotic factors causing fruit decay after harvest. Among the different varieties of mandarins, *Khasi* mandarin (*Citrus reticulata*, Blanco) is an important citrus cultivar having the highest export potential for its uniqueness in juice quality. *Khasi* mandarins (*Soh-niamntra* in *Khasi*) are cultivated over 1,600 hectares of land in the East and West *Khasi* Hills and Ri-Bhoi and Garo Hills of Meghalaya.¹ The fruit *Khasi* mandarin was awarded a Geographical Indication (GI) tag in 2014 under the Geographical Indication of Good, Registration and Protection Act, 1988 by the Government of India (Doki et al., 2019) as the climatic conditions in Meghalaya are more suitable for the production of *Khasi* mandarin compared to other contributing states (Passah and Tripathi, 2020). However, the fruit deteriorates rapidly after harvest due to microbial infections, particularly *Penicillium* rot, leading to biochemical changes and physiological aging, which ultimately reduces the fruit's edible quality. Ag NPs have been

¹ <https://nhb.gov.in/>

proven to be effective against more than 650 microorganisms, including bacteria, fungi, viruses, and nematodes (Dakal et al., 2016). Silver nanocoating is widely used in the food processing sector to extend the shelf life of many food products. Silver nanoparticles (Ag NPs) are widely used as one of the important ingredients in the food processing and packaging sector due to their strong antimicrobial qualities against diverse pathogens. Dube and Okuthe (2025) reported on the wide range of antimicrobial activities of silver nanoparticles, including their applications in food preservation and water treatment. Emamifar et al. (2010) developed low-density polyethylene (LDPE) films infused with Ag and Zn nanoparticles for storing orange juice at 4 °C. They also found that juice kept in silver- and zinc-coated packaging materials could successfully maintain the microbial population below the acceptable limit for shelf life (6 log cfu/mL) for up to 28 days of storage. In the present investigation, gluconate-stabilized silver nanocoating was explored as a coating material to enhance the shelf life of *Khasi* mandarin to minimize spoilage of the fruit and juice by eliminating post-harvest decay pathogens.

2 Materials and methods

2.1 Synthesis of gluconate-stabilized silver nanoparticles (Glu-Ag NPs)

All chemicals used in the experiments were of analytical grade. Gluconate-stabilized silver nanoparticles (Glu-Ag NPs) were synthesized by following the protocol outlined by Choudhury and Misra (2018). Briefly, 1 mL of aqueous solution of silver acetate was added dropwise into a chilled aqueous solution mixture of sodium borohydride (NaBH₄, 10 mM, 5 mL) and sodium salt of D-gluconate (1 mM, 50 mL) under continuous stirring conditions at 400 rpm. The addition rate was kept constant by a drop every 5 s. The initial colorless solution mixture turned light to brighter yellow upon the addition of silver acetate solution. The reaction mixture was kept in the dark, undisturbed, and observed for color changes. The synthesis of Glu-Ag NPs was confirmed with the help of UV-Vis spectroscopy.

Fully ripened *Khasi* mandarin fruits, without any signs of mechanical damage, were collected in sterilized polypropylene bags and brought to the laboratory for further processing. *Citrus reticulata* (*Khasi* mandarin) fruits were picked from 6-year-old trees grown in a private orchard located in Sohkhwai (GPS: latitude: 25.966865, longitude: 91.826647), Ri Bhoi, Meghalaya, India. *Khasi* mandarin (*Citrus reticulata*, Blanco) is one of the dominant cultivated species in North East India, along with other species of citrus fruits, such as *Citrus indica* and *Citrus latipes*. *Citrus reticulata* is not included in the IUCN Red list; therefore, the IUCN guidelines do not apply to the current study regarding the sample collection of experimental items. *Citrus reticulata* (*Khasi* mandarin) fruits were picked from 6-year-old trees grown in a private orchard in Sohkhwai (GPS coordinates: latitude: 25.966865, longitude: 91.826647), Ri Bhoi, Meghalaya, India.

2.2 Characterization of synthesized Glu-Ag NPs

The synthesized Glu-Ag NPs were characterized using UV-visible spectroscopy (UV-Vis), dynamic light scattering (DLS), scanning

electron microscopy (SEM), and transmission electron microscopy (TEM).

2.3 Study on the *in vitro* efficacy of Glu-Ag NPs

The *In vitro* efficacy of Glu-Ag NPs against *Penicillium italicum* (PV931913) was studied using an agar well diffusion test at different concentrations: 10, 50, 100, 250, 500, 1,000, and 5,000 ppm. All the plates were placed in a BOD incubator, and observations were recorded after 72 h to measure the zone of inhibition.

2.4 Preparation of coating solutions

The coating solution was prepared at a concentration of 250 ppm of Glu-Ag NPs in sterile distilled water and stored at ambient temperature (22 ± 2 °C). The selected oranges, as per the criteria, were first disinfected with 1% sodium hypochlorite (NaOCl) for 1 min. After disinfection, the oranges were rinsed with water and air-dried. The sterilized fruits were then immersed in the coating solution while continuously rotating at 100 rpm at ambient conditions (22 ± 2 °C) on a magnetic stirrer for a standardized exposure time of 120 s, with three replications.

Solutions for wax coating were prepared using the modified protocol outlined by Muthuselvi et al. (2020) and Isnaini and Purbiati (2021). A measure of 0.1 mL Triton X-100 was added to 500 mL of lukewarm water in a beaker. Then, 2.5 g of paraffin wax was added to 100 mL of lukewarm water in another glass beaker. Both the emulsifying water and the paraffin wax containing water were added simultaneously to another 1,000 mL glass beaker and stirred vigorously. The selected mandarins were dipped for 30 s in the prepared wax solution; then, they were stirred with a glass rod, removed, and air-dried on a sterile tray. The wax formed small, breakable pellets on the skin of the mandarins, and the treated mandarins were stored at room temperature (22 ± 2 °C) for further processing.

The untreated control was maintained by dipping the fruits in sterile water only. All the treated and untreated mandarins were replicated thrice, air-dried at room temperature (22 ± 2 °C), and were kept in a pre-sterilized plastic tray. The tray was wrapped with a sterile transparent polythene sheet with perforation to maintain humid conditions for further analysis.

2.5 Inoculation of the pathogen on the coated fruits

Artificial inoculation of pathogens was performed on both the nanocoated and uncoated fruits using a modified protocol given by Guilli et al. (2016) and Vilanova et al. (2014). Nanocoated, wax-coated, and uncoated mandarins were inoculated with *Penicillium italicum* by four different methods: M₁ = Immersion in a spore suspension of *P. italicum*, M₂: Spraying the spore suspension with sprayers, M₃: Injection of the spore suspension at four equidistant positions on the skin, and M₄: Disc inoculation method in which two discs, each of 6 mm in diameter, were placed at two equidistant positions on the skin

of both the treated and untreated mandarins. The same inoculum suspension of *P. italicum* (3.4×10^6 cfu/mL) was used for immersion, spraying, and injection methods, and a 7-day-old culture was utilized for disc inoculation.

The treatment combinations for this experiment were finalized based on the pre-standardized time for nanocoating. These combinations are listed below.

T ₁ M ₁	Nanocoated for 120 s + <i>P. italicum</i> (Immersion)
T ₁ M ₂	Nanocoated for 120 s + <i>P. italicum</i> (Spraying)
T ₁ M ₃	Nanocoated for 120 s + <i>P. italicum</i> (Injection)
T ₁ M ₄	Nanocoated for 120 s + <i>P. italicum</i> (Disc inoculation)
T ₂ M ₁	Wax coated for 30 s + <i>P. italicum</i> (Immersion)
T ₂ M ₂	Wax coated for 30 s + <i>P. italicum</i> (Spraying)
T ₂ M ₃	Wax coated for 30 s + <i>P. italicum</i> (Injection)
T ₂ M ₄	Wax coated for 30 s + <i>P. italicum</i> (Disc inoculation)
T ₃ M ₁	Uncoated + <i>P. italicum</i> (Immersion)
T ₃ M ₂	Uncoated + <i>P. italicum</i> (Spraying)
T ₃ M ₃	Uncoated + <i>P. italicum</i> (Injection)
T ₃ M ₄	Uncoated + <i>P. italicum</i> (Disc inoculation)

2.6 Statistical analysis

All the treatments were replicated three times and arranged in a completely randomized block design (CRD). Data were analyzed using two-way analysis of variance (ANOVA), with mean comparisons performed using Tukey's test at a significance level of $p < 0.05$.

2.7 Assessment of the disease severity index (%)

The data for disease severity were recorded 10th day after inoculation of the pathogen, and Percent Disease Severity Index (PDI) was assessed using the rating scale as given below.

Grade	Range of infection
0	No infection
1	1%–25% of the surface area of the fruit show disease symptoms
2	26%–50% of the surface area of the fruit show disease symptoms
3	51%–75% of the surface area of the fruit show disease symptoms.
4	>75% of the surface area of the fruit show disease symptoms.

The disease severity index (DSI) was calculated using the following formula:

$$DSI(\%) = \frac{\sum \left(\frac{\text{No. of diseased fruit in each rating category} \times \text{Severity rating}}{\text{Total No. of fruit assessed} \times \text{Highest Scale}} \right) \times 100$$

2.8 Estimation of percent fruit weight loss (% FWL)

The fruits were weighed before coating and after 10th day of coating. The findings were estimated as the percentage of weight loss using the following formula (Hazali et al., 2013)

$$\text{Weight loss}(\%) = \left(\frac{W_i - W_s}{W_i} \right) \times 100.$$

where W_i = Initial fruit weight; W_s = Fruit weight at sampling date.

2.9 Measurement of the Browning index (BI) in Khasi mandarin juice

Browning of food or fruit juice is a well-known phenomenon that occurs during the processing or storage of juices, resulting in brown pigmentation. Non-enzymatic browning (NEB) is an important quality parameter of the juice during storage, which is expressed as browning index. For the estimation of browning index, juice stored in both refrigerated and ambient storage conditions was considered. Browning index was estimated with a modified protocol given by Meydavi et al. (1977). Briefly, 10 mL of composite juice samples with different exposure times were centrifuged at 7,000 rpm for 15 min. A measure of 3 mL of supernatant was removed and placed in a second centrifuge tube, and mixed thoroughly with 3 mL of ethanol. Diluted samples were kept at room temperature and again centrifuged for 15 min with the same procedure. The absorbance of the supernatant was recorded at 420 nm with the UV-Vis spectrophotometer.

2.10 Estimation of titratable acidity (TA) of Khasi mandarin juices

Titratable acidity (TA) is generally determined by using standard NaOH (0.1 N) with phenolphthalein as an indicator and can be expressed conveniently in g acid per 100 g by using the factor appropriate to the acid. The TA was measured by following the protocol given by FSSAI (2015). It was estimated for both refrigerated (4°C) and ambient (22 ± 2°C). A measure of 10 mL of juice was diluted to 250 mL with neutralized or recently boiled water, which was titrated with 0.1 N NaOH using 0.3 mL of phenolphthalein for each 100 mL of the solution to obtain a pink endpoint. The titrated value was recorded and the amount of NaOH consumed was reported as acidity in mL 0.1 N NaOH per 100 mL. The TA was measured in terms of citric acid equivalent according to the conversion factor (1 mL 0.1 N NaOH = 0.0070 g citric acid monohydrate).

3 Results and discussions

3.1 Synthesis and characterization of Glu-Ag NPs

The gluconate-stabilized silver nanoparticles (Glu-Ag NPs) were synthesized as per the protocol of Choudhury and Misra (2018) with

a few modifications. The color of the synthesized nanoparticles changes from yellow to brown after being stored. The synthesis was further confirmed by UV–Vis, DLS, SEM, TEM, etc.

3.1.1 UV–Vis spectroscopic analysis

The synthesis of Glu–Ag NPs was confirmed with the help of UV–Vis Spectroscopy. **Figure 1A** shows the absorbance peak recorded at 410 nm, and data obtained from the spectral ranges confirmed the formation of silver nanoparticles. Silver nanoparticles generally show a UV absorbance peak between 360 nm and 500 nm (Kaman and Dutta, 2018). The SPR peak was found to be formed at 410 nm. The absorbance at 410 nm is a characteristic feature of Ag NPs that is due to the surface plasmon resonance of silver nanoparticles.

3.1.2 Dynamic light scattering (DLS)

In material physics, this technique is used to determine the size distribution profile of suspended nanoparticles. The DLS system measures the light scattering effects arising from the Brownian motion of particles in suspension. The synthesized gluconate-stabilized silver nanoparticles (Glu–Ag NPs) were sonicated for at least 5 min before analysis. This technique determined the size of 94.10 nm (**Figure 1B**) with a polydispersity index (PDI) of 0.413, which indicates the polydisperse nature of the synthesized Glu–Ag NPs. According to Hughes et al. (2015), PDI has a value between 0

and 1 and is dimensionless. Particle polydispersity maturity is indicated by a PDI value close to or equal to 1. A monodisperse system is indicated if it is closer to zero, which indicates the presence of only one particle size.

3.1.3 Scanning electron microscopy (SEM) studies

The surface morphology of synthesized silver nanoparticles was evaluated by ZEISS Scanning Electron Microscopy. The particles in the SEM images seem spherical and agglomerated (**Figure 1C**). The EDAX spectra of silver nanoparticles confirmed the formation of silver nanoparticles by attaining a peak at 2KeV.

3.1.4 Transmission electron microscopy (TEM) studies

The distribution of particle size, as well as the size of the nanoparticles were evaluated by TEM studies. TEM micrographs of Glu–Ag NPs showed particles that were dispersed neatly, had an average diameter of 24 nm, and seemed to be spherical in shape (**Figure 1D**). The crystal structure of the synthesized silver nanoparticle was determined by selected area electron diffraction (SAED). The scattered bright spot (**Figure 1E**) represents the crystalline structure of the synthesized Glu–Ag NPs. The SAED pattern obtained from TEM signifies the occurrence of (111), (200), and (220) planes in silver nanoparticles.

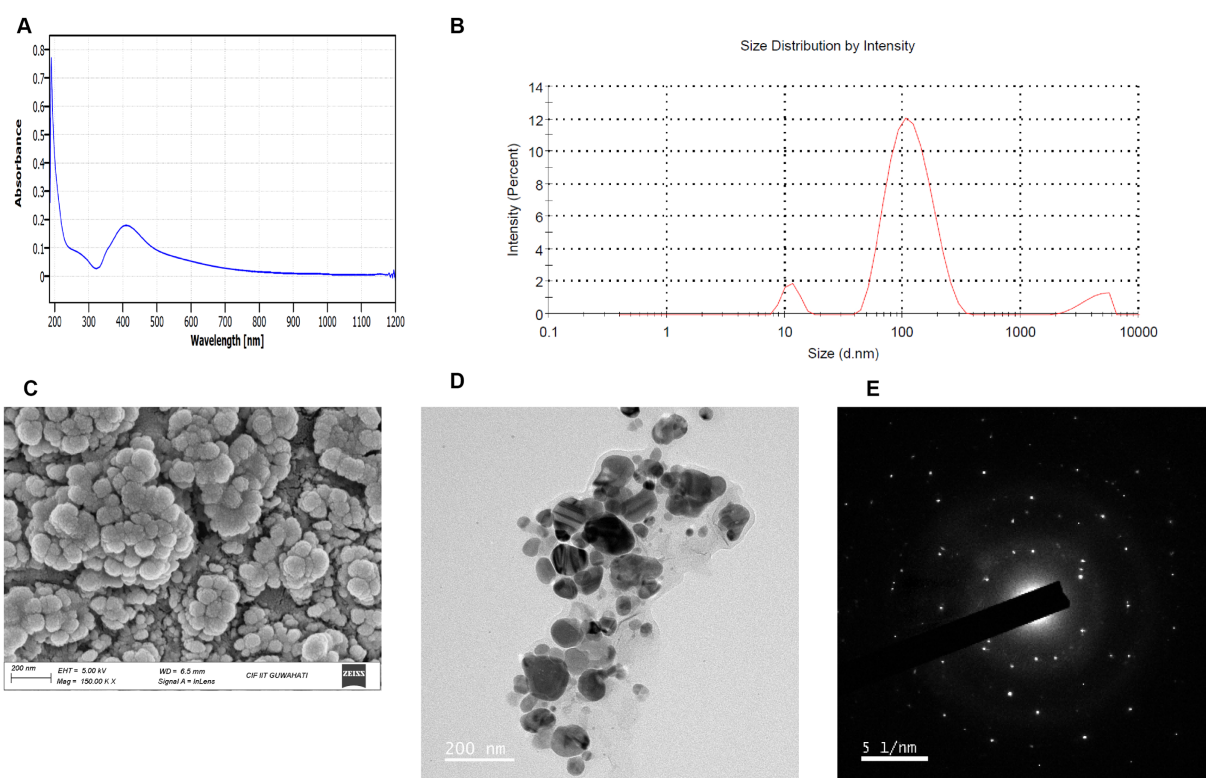


FIGURE 1

(A) UV–Vis spectra of synthesized gluconate-stabilized silver nanoparticles (Glu–Ag NPs). (B) DLS study of synthesized gluconate-stabilized silver nanoparticles (Glu–Ag NPs). (C) SEM micrograph of synthesized gluconate-stabilized silver nanoparticles (Glu–Ag NPs) at 100 kX. (D) Transmission electron microscopy (TEM) of synthesized gluconate-stabilized silver nanoparticles (Glu–Ag NPs) at 100 kX. (E) SAED of crystalline Glu–Ag NPs.

3.1.5 *In vitro* efficacy of Glu-Ag NPs against *Penicillium italicum*

As Ag NPs are well known for their antimicrobial properties, the synthesized Glu-Ag NPs showed the highest (58.23%) mycelial growth inhibition of *P. italicum* at 250 ppm (Figure 2), followed by 1,000 ppm (47.63%) and 100 ppm (47.34%) in agar well diffusion test. Hamouda et al. (2024) reported that silver nanoparticles synthesized from *Turbinaria turbinata* can inhibit 68.75% growth of *P. italicum* @ 4.5 mg/mL. Rafiq et al. (2022) reported that Ag NPs indicated high susceptibility at 200 ppm and 300 ppm against *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, and *Candida albicans*. The same concentration of Ag NPs was found to be effective against common foodborne pathogens *E. coli* and *S. aureus*. Kaman and Dutta (2018) reported the antimicrobial effect of silver nanoparticles at 100 ppm concentration against *Rhizoctonia solani*, *Fusarium oxysporum*, *Sclerotinia sclerotiorum*, and *S. rolfsii*.

3.1.6 Estimation of disease severity index (DSI) %

The highest disease severity index (DSI) (66.7%) (Figures 3A,B) was recorded in T₃, where no coating was applied, and the lowest was recorded in T₁: nanocoated for 120 s (13.9). The highest DSI was recorded in M₄: Disc method of inoculation (63.8%) (Figure 3), followed by M₃: Injection method of inoculation, while the lowest DSI was reported in M₁: Immersion (16.7%), followed by M₂: Spraying (27.8%). As Glu-Ag NPs act as a protective coating on the nanocoated mandarin, they may interact as an antimicrobial agent against the targeted pathogen. Silver nanoparticles cause cell membrane disintegration by forming “pits” on the pathogenic microbes’ cell surface or penetrate inside the cell membrane by diffusion, endocytosis, or electrostatic attraction, causing DNA damage or loss of replication ability (Morones et al., 2005; Sondi and Sondi, 2004).

Moreover, ROS-induced oxidative stress is an important antimicrobial mechanism for Ag NPs (Rao et al., 2024). This reduces their disease-causing potency.

3.1.7 Estimation of fruit weight loss (%)

The results showed that the highest fruit weight loss (12.54%) was recorded in T₃: uncoated control, while the lowest (3.00%) was recorded in T₁: nanocoated for 120 s, followed by T₂: wax coated for 30 s (4.64%). The treatment effect was found to be significant ($p < 0.005$), while different methods of inoculation of the pathogen and the interaction between the treatments of methods of pathogen inoculation were found to be non-significant (Table 1; Figure 4A). Transpiration or evaporation of water from the harvested fruit results in direct quantitative loss in terms of fruit weight and appearance, such as shriveling, wilting, textural quality such as softening, flaccidity, and loss of juiciness. In the present experiment, the highest fruit weight loss was recorded in uncoated fruits due to the absence of any protective barrier in the uncoated fruits, thereby increasing the respiration rate. In T₁: nanocoated for 120 s, the lowest fruit weight loss (3.0%) was recorded, which may be due to the low transpiration rate.

3.1.8 Effect of Glu-Ag NPs on titratable acidity (TA) of mandarin juices

In the present study titratable acidity in terms of citric acid (0.061 g/100 g) was found to be the highest in the juice extracted from the T₃: uncoated control, stored at ambient condition ($22 \pm 2^\circ\text{C}$) and the lowest (0.031 g/100 g) was recorded in the juice extracted from the T₁: nanocoated mandarins stored in refrigerated conditions (4°C) (Figure 4B; Table 2). This may be due to the coating effect that probably inhibited the enzyme activity

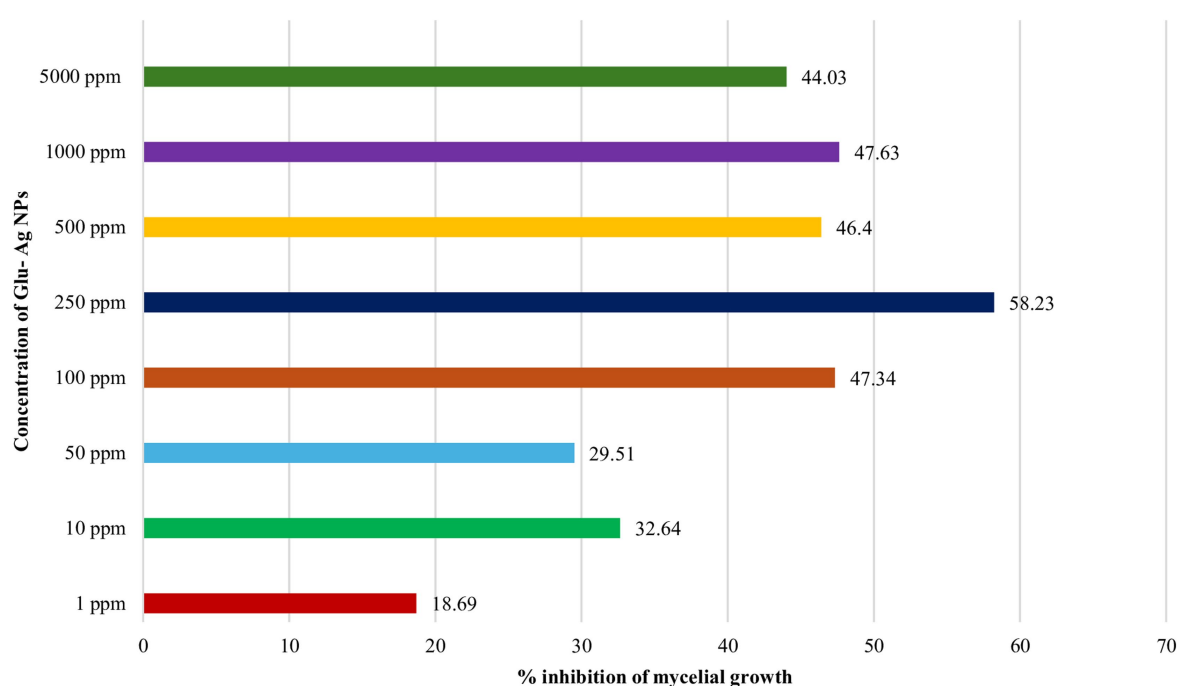


FIGURE 2
Zone of inhibition of Glu-Ag NPs against *Penicillium italicum* at different concentrations.

responsible for organic acid metabolism and thereby slowed down the rate of acid production. The increase in acidity in the control may be the result of the fermentation process (Win et al., 2021). Prusky et al. (2004) reported an increase in production of citric acid due to the infection of *Penicillium* spp. on citrus and apple. In the present study, the highest disease severity index (66.7%) was recorded in T₃: uncoated mandarin. Due to the higher infection rate in uncoated mandarins, the amount of citric acid production was found to be higher. Prusky et al. (2004) reported that the more the infection by *Penicillium* sp., the higher the production of citric acid.

3.1.9 Effect of Glu-Ag NPs on Browning index (BI) of juices of Khasi mandarin

The results show that the development of brown color was clearly visible in the juice stored at ambient conditions ($22 \pm 2^\circ\text{C}$) and it was more prominent after 12 weeks of storage. Juices stored at 4°C

temperature recorded the lowest BI (0.209) in T₁: Nanocoated for 120 s, followed by T₂: wax coated (0.296) and the highest was recorded at T₃: Uncoated control (0.608) stored at ambient conditions ($22 \pm 2^\circ\text{C}$) (Table 3; Figure 4C). Disc inoculation (M₄) recorded the highest BI (0.684) at ambient condition and at 4°C , the BI was recorded as 0.439. Lowest (0.223) BI was recorded in both immersion (M₁) and injection (M₃) method of inoculation in the juice stored at 4°C . In case of treatments, the lowest BI (0.081) was recorded in T₁: nanocoated for 120 s with immersion (M₁) method of inoculation and the highest BI (0.975) was recorded in T₃: Uncoated with disc method of inoculation (M₄) in the juice stored at $22 \pm 2^\circ\text{C}$. Non-enzymatic browning (NEB) is an important quality parameter of the juice during storage. Soluble compounds in orange juice concentrate, such as amino acids and sugars, decompose and result in the production of furfural, 5-hydroxymethyl furfural (HMF), which is responsible for juice browning (Bharate and Bharate, 2012), and this browning can also be visualized with the naked eye for longer storage. Khan et al. (2016) reported the use of silver nanoparticles to minimize browning of white cabbage by inhibiting the enzyme tyrosinase. In the present study, the lowest BI was recorded in the juice extracted from the nanocoated mandarins. This may be due to the effect of nanocoating in lowering down of respiration rate and delaying the rise of ethylene (Solomos, 1997). Silver nanocoating acts as a barrier to oxygen access and thereby less oxidation occurs by creating an environment of low O₂ and High CO₂ (Li et al., 2011). Horison et al. (2022) found lower BI in fresh-cut apples coated with carrageenan, ascorbic acid, and ZnO nanoparticles.

3.2 Shelf life study of nanocoated, wax-coated, and uncoated mandarins

For studying the shelf life of nanocoated, wax-coated, and uncoated mandarin without artificial inoculation, freshly harvested fruits were used for nanocoating for 120 s, wax coating for 30 s, and uncoated fruits were maintained as a control. All the mandarins were kept in a sterilized tray and kept in ambient temperature ($22 \pm 2^\circ\text{C}$) to compare the effect of nanocoating with the normally practiced wax coating. Results showed that the nanocoated fruits remain free from natural infection up to 32 days in ambient temperature ($22 \pm 2^\circ\text{C}$) and 45 days in refrigerated conditions (4°C). From 32 days onwards, shrinkage of the skin was observed in nanocoated fruits, with skin color turned from bright orange to pale orange. The nanocoated fruits stored in refrigerated conditions become soft, light, pale skin, and prominent shrinkage of the skin occurs after 45 days of storage. Though the progress of the disease

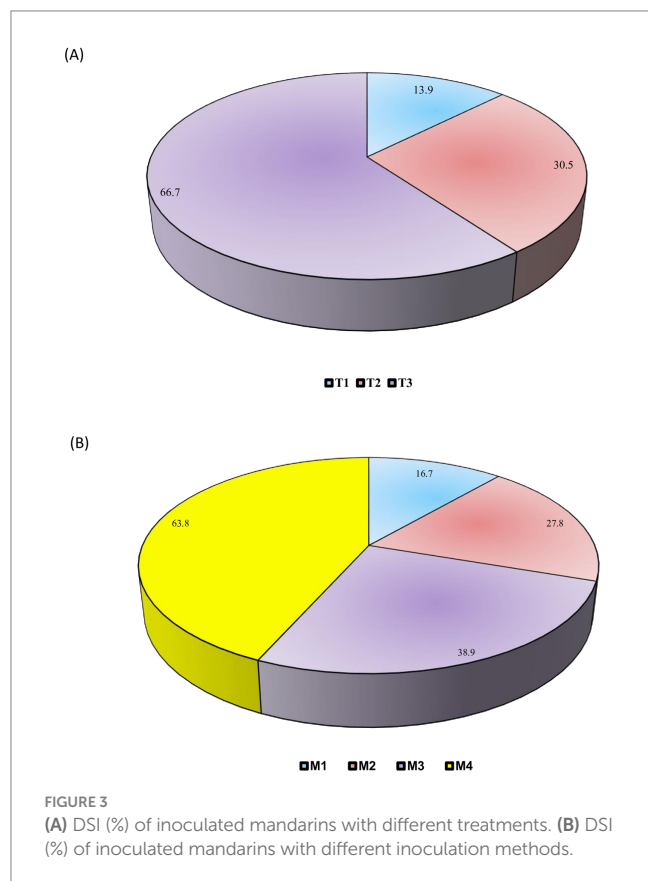
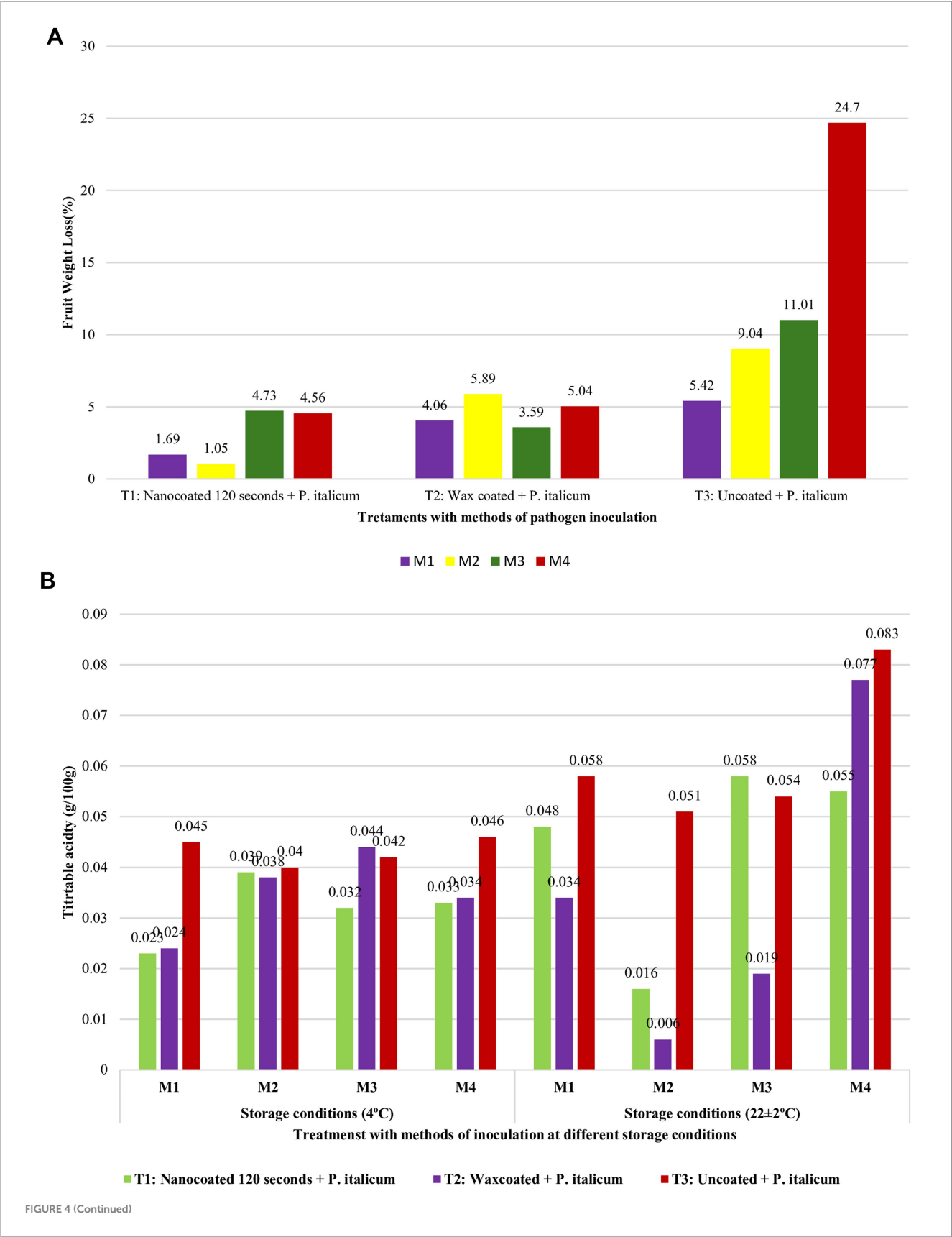


TABLE 1 Estimation of fruit weight loss (%) of nanocoated, wax-coated, and uncoated mandarins in different methods of pathogen inoculation.

Treatments	Fruit weight loss (%) of Khasi mandarin					p-value	F-value
	M1	M2	M3	M4	Mean of three replicates $\pm$ SEM		
T ₁ : Nanocoated 120 s + <i>P. italicum</i>	1.69	1.05	4.73	4.56	3.008 ^{ab} $\pm$ 0.585	0.2289	1.4746
T ₂ : Wax coated + <i>P. italicum</i>	4.06	5.89	3.59	5.04	4.646 ^b $\pm$ 0.893		
T ₃ : Uncoated + <i>P. italicum</i>	5.42	9.04	11.01	24.70	12.545 ^a $\pm$ 3.449		
Mean	3.726 ^a $\pm$ 0.884	5.327 ^a $\pm$ 2.116	6.444 ^a $\pm$ 2.380	11.435 ^a $\pm$ 4.183	6.733		

*Data followed by the same superscript letter in each column are statistically at par ($p < 0.005$) using Tukey's statistical test.



was slower in wax-coated fruit, it spoiled within 25 days. While uncoated mandarins became soft, rotten, and spoiled within 20 days of storage (Figure 5) in an ambient condition ($22 \pm 2^\circ\text{C}$). Thus, by nanocoating with Glu-Ag NPs for 120 s, the shelf life of *Khasi* mandarin can be extended for 32 days. Nanocoating can enhance the hydrophobicity and reduce the surface roughness of the sample

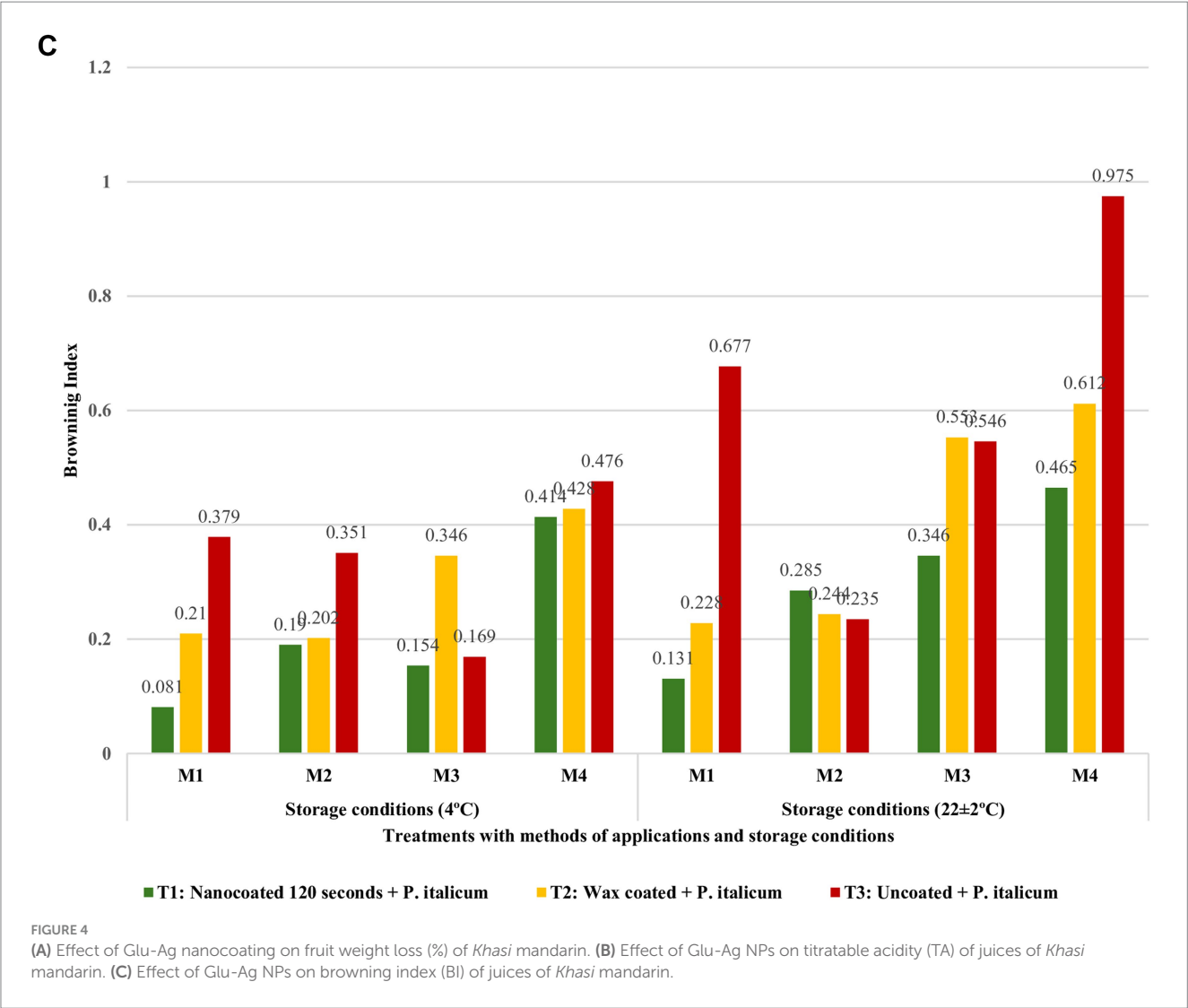


TABLE 2 Effect of Glu-Ag NPs on titratable acidity (TA) of juices of *Khasi* mandarin stored in two different storage conditions with different methods of inoculation.

Treatments	Methods of pathogen inoculations					P value	F value
	M1	M2	M3	M4	Mean of three replicates $\pm$ SEM		
Storage conditions (4°C)							
T ₁ : Nanocoated 120 s + <i>P. italicum</i>	0.023	0.039	0.032	0.033	0.031 ^{*c} $\pm$ 0.001	<0.0001	52.469
T ₂ : Wax coated + <i>P. italicum</i>	0.024	0.038	0.044	0.034	0.034 ^b $\pm$ 0.002		
T ₃ : Uncoated + <i>P. italicum</i>	0.045	0.040	0.042	0.046	0.043 ^a $\pm$ 0.000		
Mean	0.030 ^b $\pm$ 0.003	0.038 ^a $\pm$ 0.006	0.039 ^a $\pm$ 0.001	0.037 ^a $\pm$ 0.002	0.036		
Storage conditions (22 $\pm$ 2 °C)							
T ₁ : Nanocoated 120 s + <i>P. italicum</i>	0.048	0.016	0.058	0.055	0.044 ^b $\pm$ 0.005	0.0003	6.599
T ₂ : Wax coated + <i>P. italicum</i>	0.034	0.006	0.019	0.077	0.034 ^c $\pm$ 0.008		
T ₃ : Uncoated + <i>P. italicum</i>	0.058	0.051	0.054	0.083	0.061 ^a $\pm$ 0.004		
Mean	0.046 ^b $\pm$ 0.005	0.024 ^a $\pm$ 0.006	0.043 ^b $\pm$ 0.006	0.071 ^a $\pm$ 0.005	0.046		

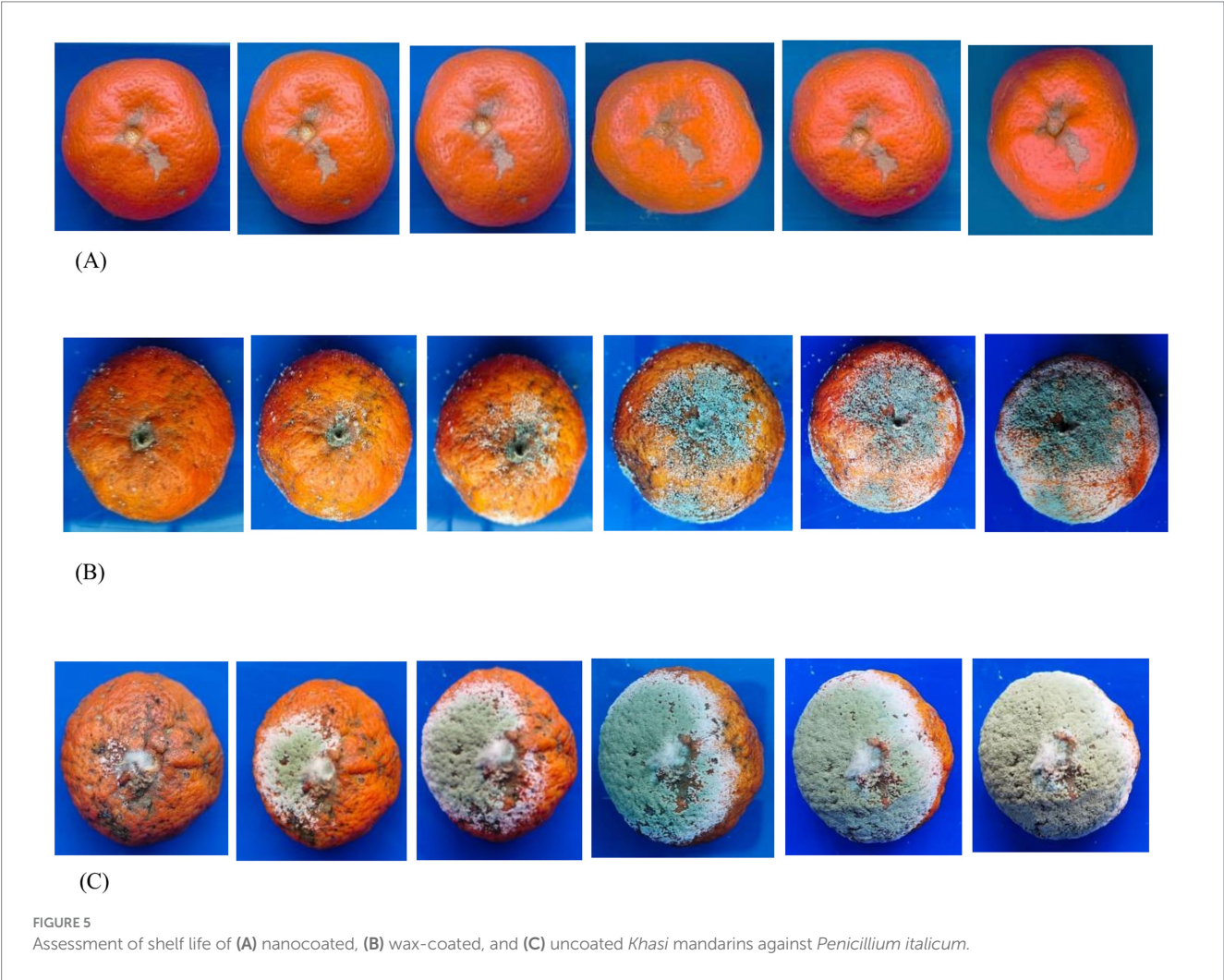
*Data followed by the same superscript letter in each column are statistically at par ($p < 0.005$) using Tukey's statistical test.

by filling the microstructured pores, including lenticels, with the gluconate-stabilized silver nanoparticles, thereby restricting gas exchange, respiration, and transpiration. The increased hydrophobicity or reduced wettability is affected by the ionic bonds

TABLE 3 Effect of Glu-Ag NPs on browning index (BI) of juices of *Khasi* mandarin stored in two different storage conditions with different methods of inoculation.

Treatments	Browning index (BI) of <i>Khasi</i> mandarin juice					<i>p</i> value	<i>F</i> Value
	M1	M2	M3	M4	Mean of three replicates $\pm$ SEM		
Storage conditions (4 °C)							
T ₁ : Nanocoated 120 s + <i>P. italicum</i>	0.081	0.19	0.154	0.414	0.209 ^{b*} $\pm$ 0.037	0.0005	6.113
T ₂ : Wax coated + <i>P. italicum</i>	0.210	0.202	0.346	0.428	0.296 ^a $\pm$ 0.037		
T ₃ : Uncoated + <i>P. italicum</i>	0.379	0.351	0.169	0.476	0.343 ^a $\pm$ 0.034		
Mean	0.223 ^b $\pm$ 0.054	0.247 ^b $\pm$ 0.026	0.223 ^b $\pm$ 0.031	0.439 ^a $\pm$ 0.016			
Storage condition: 22 $\pm$ 2 °C							
T ₁ : Nanocoated 120 s + <i>P. italicum</i>	0.131	0.285	0.346	0.465	0.306 ^c $\pm$ 0.036	<0.0001	1277.198
T ₂ : Wax coated + <i>P. italicum</i>	0.228	0.244	0.553	0.612	0.409 ^b $\pm$ 0.052		
T ₃ : Uncoated + <i>P. italicum</i>	0.677	0.235	0.546	0.975	0.608 ^a $\pm$ 0.080		
Mean	0.345 ^c $\pm$ 0.084	0.254 ^d $\pm$ 0.007	0.481 ^b $\pm$ 0.034	0.684 ^a $\pm$ 0.075			

*Data followed by the same superscript letter in each column are statistically at par (*p* <0.005) using Tukey's statistical test.



between the surface and free ions of the fluids. Ali et al. (2018) have mentioned that the contact angle of the water molecule in nanocoated fruit is less due to the existence of the nanocoating layer on the fruit. The nanocoated fruits thus overcome pathogen

infection by minimizing its proliferation in water stress conditions on the surface of the nanocoated fruits. Moreover, the dual antimicrobial action of silver and gluconate inhibits pathogen infection and thereby enhances shelf life.

4 Conclusion

The present research focused on the application of gluconate-stabilized silver nanocoating, wax coating, and without coating on *Khasi* mandarin to determine its effects on fruit weight loss, disease severity index, titratable acidity, and browning index of *Khasi* mandarin juice. On application of nanocoating with Glu-Ag nanoparticles, DSI was found to be lowest (13.9) with the lowest fruit weight loss (3.00%) and titratable acidity, but with the highest browning index. Moreover, the coating effect reduces the shrinkage of the skin, maintains the color of the fruit. Thus, this research recommends that the application of gluconate-stabilized silver nanocoating can enhance the shelf life of *Khasi* mandarin up to 32 days in ambient conditions by lowering the disease severity index. Ease of chemo-centric synthesis of nanoparticles and their application with dual antimicrobial action of gluconate-stabilized silver nanoparticle strongly inhibits the post-harvest pathogen proliferation. Its coating effect also enhances the shelf life of the product. Thus, the present findings opens up new directions on toxicity assessment of synthesized gluconate-stabilized silver nanoparticle for its further application in food processing and preservation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DD: Conceptualization, Formal analysis, Methodology, Writing – original draft. PD: Investigation, Supervision, Visualization, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

References

- Ali, N., Teixeira, J. A., Addali, A., Al-Zubi, F., Shaban, E., and Behbehani, I. (2018). The effect of aluminium nanocoating and water pH value on the wettability behavior of an aluminium surface. *Appl. Surf. Sci.* 443, 24–30. doi: 10.1016/j.apsusc.2018.02.182
- Bharate, S. S., and Bharate, S. B. (2012). Non-enzymatic browning in citrus juice: chemical markers, their detection and ways to improve product quality. *J. Food Sci. Technol.* 51, 2271–2288. doi: 10.1007/s13197-012-0718-8
- Choudhury, C., and Misra, T. K. (2018). Gluconate stabilized silver nanoparticles as a colorimetric sensor for Pb²⁺. *Colloids Surf. A Physicochem. Eng. Asp.* 545, 179–187. doi: 10.1016/j.colsurfa.2018.02.051
- Dakal, T. C., Kumar, A., Majumdar, R. S., and Yadav, V. (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Front. Microbiol.* 7:1831. doi: 10.3389/fmicb.2016.01831
- Doki, N., Eya, C., and Tugghba, M. (2019). Determinants of post-harvest losses of orange in selected local government areas of Benue state. *Int. J. New Econom. Soc. Sci.* doi: 10.5604/01.3001.0013.8106
- Dube, E., and Okuthe, G. E. (2025). Silver Nanoparticle-Based Antimicrobial Coatings: Sustainable Strategies for Microbial Contamination Control. *Microbiol. Res.* 16:110. doi: 10.3390/microbiolres16060110
- Emamifar, A., Kadivar, M., Shahedi, M., and Soleimani, Z. S. (2010). Evaluation of nanocomposite packaging containing Ag and ZnO on shelf life of fresh orange juice. *Innov. Food Sci. Emerg. Technol.* 11, 742–748. doi: 10.1016/j.ifset.2010.06.003
- Food Safety and Standards (Food Products Standards and Food Additives) Regulations (2011). Available online at: https://www.fssai.gov.in/upload/uploadfiles/files/Compendium_Food_Additives_Regulations_20_12_2022.pdf, p.774.
- FSSAI (2015). Manual of methods of analysis of foods, fruits and vegetables products, Method No. 2.4. New Delhi: FSSAI, Ministry of Health and Family Welfare, Govt. of India, 12.
- Guilli, E. L. M., Hamza, A., Christophe, C., Mohammed, I., and Essaid, A. B. (2016). Effectiveness of postharvest treatment with chitosan to control citrus green mould. *Agriculture* 2. doi: 10.3390/agriculture6020012
- Hamouda, R. A., Almaghrabi, F. Q., Alharbi, O. M., Alharbi, A. D. M., Alsulami, R. M., and Alhumairi, A. M. (2024). Antifungal activities of biogenic silver nanoparticles mediated by marine algae: *in vitro* and *in vivo* insights of coating tomato fruit to protect against *Penicillium italicum* blue mold. *Mar. Drugs* 22:225. doi: 10.3390/md22050225

Acknowledgments

The authors highly acknowledge the College of Post-graduate Studies in Agricultural Sciences, Umiam, Central Agriculture University (Imphal) for providing the facility for the research work.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1711722/full#supplementary-material>

- Hazali, N., Ahmad, T. A., Md Nor, N., Ibrahim, M., and Adros, Y. M. N. (2013). Physicochemical characteristics of belimbing dayak (*Baccaurea angulata*) juice beverages. *EIJST* 2, 203–210. doi: 10.1016/j.ijfoodmicro.2014.02.022
- Horison, R., Sulaiman, F. O., Alfredo, D., and Wardana, A. A. (2022). Browning inhibition of fresh-cut apple by coating carrageenan/ascorbic acid/ ZnO nanoparticles. *Food Res.* 6, 368–373. doi: 10.26656/fr.2017.6(2).056
- Hughes, M. J., Budd, M. P., Grieve, A., Dutta, P., Tiede, K., and Lewis, J. (2015). Highly monodisperse, lanthanide-containing polystyrene nanoparticles as potential standard reference materials for environmental “nano” fate analysis. *J. App. Polym. Sci.* 132, 1–24. doi: 10.1002/app.42061
- Isnaini, L., and Purbiati, T. (2021). Effect of waxing and packaging method on the quality of Pontianak tangerine. *IOP Conf. Ser. Earth Environ. Sci.* 759:012018. doi: 10.1088/1755-1315/759/1/012018
- Kaman, P., and Dutta, P. (2018). Synthesis, characterization and antifungal activity of biosynthesized silver nanoparticle. *Indian Phytopathol.* 72, 79–88. doi: 10.1007/s42360-018-0081-4
- Khan, A. U., Wei, Y., Ahmad, A., Ul Haq, K. Z., Shahab, K., Nawshad, M., et al. (2016). Enzymatic browning reduction in white cabbage, potent antibacterial and antioxidant activities of biogenic silver nanoparticles. *J. Mol. Liq.* 215, 39–46. doi: 10.1016/j.molliq.2015.12.019
- Kumar, N., Khan, A. A., Pyngrope, D., Alanzi, A. M., Upadhyay, A., and Shukla, S. (2024). Development and characterization of novel starch (mango kernel and litchi seed) based active edible coatings and films using ultrasonication effects on postharvest shelf life of *Khasi* mandarins. *Sustain. Chem. Pharm.* doi: 10.1016/j.scp.2024.101610
- Li, X., Li, W., Jiang, Y., Ding, Y., Yun, J., Tang, Y., et al. (2011). Effect of nano-ZnO-coated active packaging on quality of fresh-cut ‘Fuji’ apple. *IJFST*. doi: 10.1111/j.1365-2621.2011.02706.x
- Meydav, S., Saguy, I., and Kopelman, I. J. (1977). Browning determination in citrus products. *J. Agric. Food Chem.* doi: 10.1021/jf60211a030
- Morones, J. R., Elechiguerra, J. L., Camacho, A., Hotl, K., Kouri, J. B., Ramirez, J. T., et al. (2005). The bactericidal effect of silver nanoparticles. *Nano* 16, 2346–2353. doi: 10.1088/0957-4484/16/10/059
- Muthuselvi, R., Kumar, P. N., Jagathiothi, N., Rajesh, R., Spices, S., Krishnakumare, B., et al. (2020). Importance of edible wax coatings in fruits and vegetables. *Indian. Farmers.* 7, 1006–1009.
- Passah, S., and Tripathi, A. K. (2020). Economics of Khasi mandarin cultivation in Meghalaya: Analysis of economics feasibility and constraints faced by farmers during its cultivation. *Ind. J. Hill Farming.* 33, 267–279.
- Prusky, D., McEvoy, J. L., Saftner, R., Conway, W. S., and Richard, J. (2004). Relationship between host acidification and virulence of *Penicillium spp.* on apple and citrus fruit. *Phytopathology* 94, 44–51. doi: 10.1094/phyto.2004.94.1.44
- Rafiq, A., Tehseen, S., Khan, T. A., et al. (2022). Biosynthesis of silver nanoparticles from novel *Bischofia javanica* plant loaded chitosan hydrogel: as antimicrobial and wound healing agent. *Biomass Convers.* 13, 1–11. doi: 10.1007/s13399-022-02960-w
- Rao, M. M. V., Mohammad, N., Banerjee, S., and Khanna, P. K. (2024). Synthesis and food packaging application of silver nano-particles: a review. *Hybrid Adv.* 6:100230. doi: 10.1016/j.hybadv.2024.100230
- Solomos, T. (1997). “Principles underlying modified atmosphere packaging” in Minimally processed refrigerated fruits and vegetables. ed. R. C. Wiley (New York, USA: Chapman and Hall).
- Sondi, I., and Sondi, S. B. (2004). Silver nanoparticles as antimicrobial agent: a case study on *E. coli* as a model for gram-negative bacteria. *J. Colloid Interface Sci.* 275, 177–182. doi: 10.1016/j.jcis.2004.02.012
- Vilanova, L., Viñas, I., Torres, R., Usall, J., Buron-Moles, G., and Teixidó, N. (2014). Acidification of apple and orange hosts by *Penicillium digitatum* and *Penicillium expansum*. *Int. J. Food Microbiol.* doi: 10.1016/j.ijfoodmicro.2014.02.022
- Win, N. N. C., Soe, T. T., Kar, A., Soe, Y. Y., and Lin, M. (2021). Effects of syrup solution with different concentrations of citric acid on quality and storage life of canned litchi. *OALibJ* 8, 1–16. doi: 10.4236/oalib.1108033