



RESEARCH ARTICLE

Impact of silver nanoparticles infused biopolymer coatings on post-harvest quality attributes of guava

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Abstract

Guava (*Psidium guajava* L.) is a climacteric fruit characterised by sustained ethylene production even after ripening, which induces rapid physiological and biochemical changes, thereby reducing shelf-life and increasing susceptibility to chilling injury and microbial spoilage during storage. This underlines the imperative need for an innovative method to overcome postharvest losses. This work attempts to bridge the research gaps to improve the post-harvest shelf life and improve the quality attributes of guava fruits by coating it with different polymers imbedded with antimicrobial silver nanoparticles (AgNPs). The antimicrobial efficiency of AgNPs peaked at the concentration of 100 µg mL⁻¹ with the inhibition zone of 33 mm against postharvest pathogen *Aspergillus flavus* using agar well diffusion method. Biopolymer coatings like beeswax, xanthan gum, gelatin and guar gum which are naturally available, edible and eco-friendly, act as an impervious barrier against water loss, improve the peel coloration and maintain the firmness and texture. These AgNPs imbedded biopolymer coatings created an immense impact on post-harvest quality attributes like titratable acidity (TA), reducing and non-reducing sugars. The best results were observed in the T₂ (Beeswax + AgNPs) as revealed by the highest TA of 0.38 %, lowest decay rate of 60 % and lowest reducing and non-reducing sugars of 3.02 % and 2.65 % on the 12th day after imposing the treatments. These coatings not only act as a barrier against water loss but also reduce respiration, slow down the metabolic rate, and prevent microbial decay, which leads to a better acid–sugar balance, thereby imparting improved sensory attributes.

Keywords: antimicrobial; biopolymers; guava; shelf life; silver nanoparticles

Introduction

Guava (*Psidium guajava* L.) belongs to the family Myrtaceae and is widely cultivated in tropical and subtropical regions. The fruits are highly perishable due to their high moisture content (approximately 80 %). Despite this limitation guava holds significant commercial value owing to its affordable price high nutritional quality and pleasant flavour and is therefore commonly referred to as the “poor man’s apple.” Guava is particularly rich in nutrients especially vitamin C (228.3 mg 100 g⁻¹) along with other vitamins such as niacin pantothenic acid thiamine riboflavin and vitamin A as well as appreciable amounts of minerals including phosphorus calcium and iron (1).

Guava is prone to postharvest losses due to its thin skin rapid moisture loss and quick deterioration in fruit texture which facilitates easy pathogen invasion. It is a climacteric fruit that reaches its respiratory peak shortly after harvest making it highly perishable in the early postharvest period. Another major constraint is chilling injury during storage. Being metabolically active after harvest guava undergoes rapid degradation of sugars phenols flavonoids and ascorbic acid leading to loss of texture softening browning and decay (2). Guavas are susceptible to chilling injury when stored below 6 °C and symptoms observed are

wrinkling, pitting, lignification, browning, softening of the fruit surface or flesh, flooded patches, failure to mature, increased sensitivity to fungal decay and rapid decomposition (3). The occurrence of mechanical injury in guava fruits facilitates the entry of microorganisms causing spoilage which leads to brown or black pitting peel browning tissue softening and ultimately fruit decay. Major postharvest pathogens such as *Colletotrichum* spp. causing anthracnose and *Aspergillus flavus* causing soft rot significantly limit the storage life of guava fruits (4 5).

Nearly 5–39 % of horticultural products were lost due to post-harvest losses in India and 15.88 % of guava fruits were lost during the during the post harvest handling period. It will affect Indian economy, because the entire cost of the fruit losses worth of crores of rupees (6). Due to the low storability or poor shelf-life, high sensitivity towards cold storage and microbial decay, guava fruit needs an innovative method to overcome postharvest losses. One among the innovative method is usage of nanomaterials in combination with different biopolymers. Biopolymers are eco-friendly, sustainable alternative to synthetic preservatives. Biopolymer coated fruits maintain their texture and nutrients, remain fresh for a longer period, preventing water loss and microbial spread.

All the biopolymers used in the study are locally available, edible, cheap, biodegradable and in plenty. Among these biopolymers, beeswax attracts the most attention due to its hydrophobic nature. It forms a water-repellent barrier that minimizes transpiration and weight loss due to its lipid-based structure. Hydrophilic coatings such as gelatin, xanthan gum and guar gum improve fruit shelf life during postharvest storage because of their good film-forming ability, role as carriers of active compounds and their edible and biodegradable properties (7). Silver nanoparticles (AgNPs) combined with biopolymer coated fruits showed high shelf life due to their high anti-microbial nature by inhibiting the growth of microbes which cause postharvest disease (8). However, the use of AgNPs in postharvest applications has gained attention due to their antimicrobial properties and their role in extending shelf life. A maximum threshold level of $50 \mu\text{g kg}^{-1}$ has been reported for the use of AgNPs in the food industry (9).

Our study aims to evaluate the potential of green synthesised AgNPs against the fungus *A. flavus* and to assess the postharvest quality attributes of guava fruits coated with AgNPs combined with different biopolymers. This study was taken up after a thorough evaluation of the available literature, identifying the research gaps and addressing the same using biopolymer coatings and AgNPs. The objectives of the work are (a) to estimate the efficacy of coatings in reducing microbial decay, (b) to determine whether physicochemical properties (sugars and acidity) are maintained during storage, (c) to enhance shelf life, and (d) to prolong marketable life under storage conditions.

Materials and Methods

This project which involves an interdisciplinary post-harvest approach was taken up at the Horticulture Laboratory, Pathology Laboratory and Nanotechnology Central Laboratory at Karunya Institute of Technology and Sciences in Coimbatore. Matured, medium sized “Lucknow-49” variety of uniform size and maturity guava fruits were purchased from Ayakudi farm in Coimbatore district, Tamil Nadu.

Green synthesis of silver nanoparticles

About 10 g chopped neem leaves in 100 mL of distilled water kept it in water bath maintained at 80°C for 45 min and then filtered using Whatman filter paper No.1. Subsequently, the extract of neem leaf was mixed with silver nitrate solution (1 mM) in the ratio of 1: 9 and heated for 30 min. The colour change of solution from yellow to dark brown confirmed the formation of AgNPs. Then the solution was centrifuged at 3000 rpm for 10 min and lyophilised to obtain a AgNPs in powder form. The synthesised AgNPs were confirmed by using various techniques like Zeta potential, UV-visible spectroscopy, X-ray diffraction (XRD) and scanning electron microscopy (SEM) (10).

Antimicrobial activity of biosynthesised silver nanoparticles

The antimicrobial efficacy of biosynthesised AgNPs was evaluated using Agar well diffusion method (11). The tested organism, *A. flavus* (NFCCI-3812) was obtained from National Fungal Culture Collection of India-Agharkar Research Institute (NFCCI-ARI) in Pune, India. The procured culture was maintained using potato dextrose agar (PDA) slant at 4°C for further use. Different concentration of the biosynthesised AgNPs at 15, 30, 45, 60, 75, 90 and $100 \mu\text{g mL}^{-1}$ were tested against *A. flavus* through agar well diffusion method along with the positive (carbendazim 100 ppm) and negative (distilled

water) control.

Preparation of coating materials

Addition of AgNPs solution at $100 \mu\text{g mL}^{-1}$ into biopolymer solution was done in the ratio of 1:9 (1 part of AgNP and 9 parts of biopolymer) using burette and magnetic stirrer for uniform distribution. Gelatin solution was prepared by dissolving 5% gelatin powder and adding 1.5 mL glycerol as a plasticiser in distilled water (12). Xanthan gum solution was prepared using 4% xanthan gum powder with 2 mL glycerol in distilled water (13). Guar gum solution was prepared by dissolving 2 g guar gum powder in 100 mL distilled water (14). Dipping method was used to coat the fruits and were kept on paper plates except in the case of beeswax where a brushing method was adopted to form a thin, uniform coating and the fruits were allowed to dry at room temperature (relative humidity of 67.8%, maximum temperature of 34.9°C and minimum temperature of 17.8°C). The different postharvest treatments in the study were T₁: Control, T₂: Beeswax + AgNPs, T₃: Gelatin + AgNPs, T₄: Guar gum + AgNPs and T₅: Xanthan gum + AgNPs. The control fruits were just washed with distilled water only.

Effects of AgNPs with biopolymers coating on post-harvest quality attributes of guava

Reducing and non-reducing sugars

Reducing and non-reducing sugars content was analysed using the method described by AOAC (15).

Titrateable acidity

The titrateable acidity was estimated by using the method outlined in AOAC (15).

Fruit decay

The fruit decay was expressed in percentage of visual surface deterioration of the fruit due to the softening of the texture, colour change and development of microorganisms on the surface (16).

Statistical analysis

The experiment was conducted as a completely randomised design (CRD) with 5 treatments replicated 4 times and total of seven fruit samples were used per treatment per replication (Fig. 1). (17).

Results and Discussion

In vitro efficacy of silver nanoparticles on mycelial growth of *Aspergillus flavus*

Fruits are highly perishable, nutritious and they create an optimum environment for microbial growth, making contamination a major problem during preservation. In developing countries, 20–50 % of fruits and vegetables are lost during postharvest storage due to microbial decay and poor handling, but in developed countries it is 5–35 % (18). The incidence of decay due to *A. flavus* is high with powdery yellowish-green mold symptom, leading to fruit rotting. Fruit decay due to this fungus in guava fruits is reported as 26.67 % and infection affects both the physical and chemical properties of the fruit (5).. Besides, *A. flavus* produce aflatoxins (B1) which are acute toxic, mutagenic, carcinogenic, immunosuppressive and teratogenic. Out of 600000 liver carcinogenic cases reported each year worldwide, 25200–155000 cases were estimated due to aflatoxins produced by *A. flavus* infection (19). *Aspergillus flavus* enter the fruits through wounds, spread by releasing spores, produce enzymes which degrades cell wall and produce

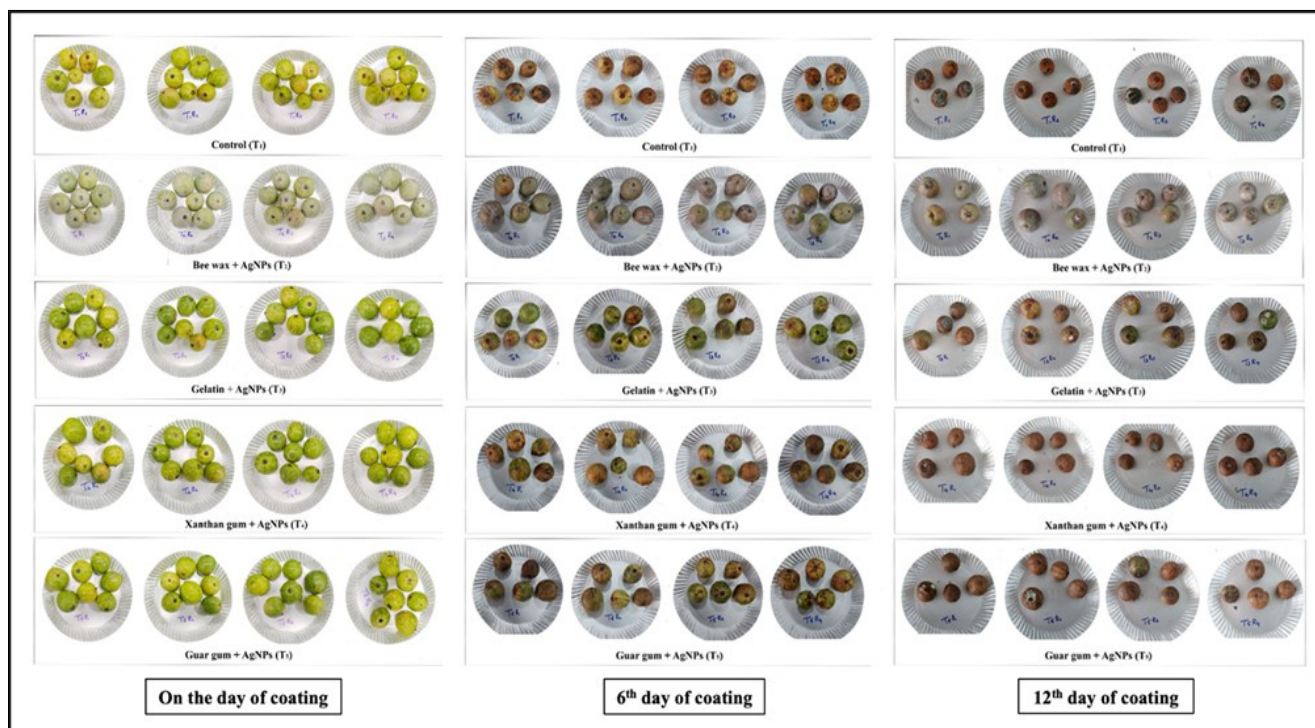


Fig. 1. Guava fruits coated with different biopolymer embedded silver nanoparticles (AgNPs).

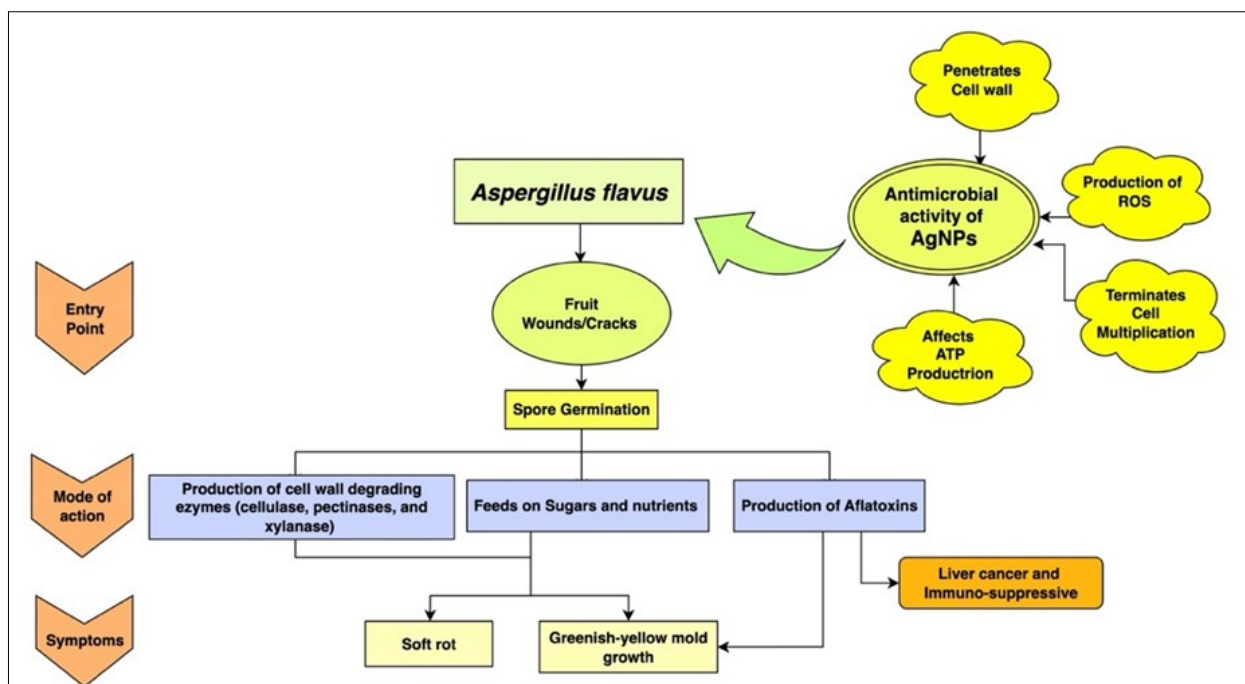


Fig. 2. Fruit degrading activity of *Aspergillus flavus* and antimicrobial activity of silver nanoparticles (AgNPs).

aflatoxins. Finally, the infected fruits show the symptom of greenish-yellow mould, soft rot and leading to fruit decay (Fig. 2) (20).

An antimicrobial study was conducted against the postharvest pathogen *A. flavus* due to the limited number of reports on the occurrence of this fungus in guava fruit and because the aflatoxins produced by this fungus are harmful to human health. The different concentration green-synthesised AgNPs revealed significant inhibition zones, indicating their antimicrobial activity. The highest inhibition zone of 33 mm was observed in 100 $\mu\text{g mL}^{-1}$ concentration (T_7) and the lowest was in 15 $\mu\text{g mL}^{-1}$ (T_1) as 8 mm, which is furnished in Fig. 3. A significant reduction in the zone of inhibition was observed in other treatments with lower concentrations of AgNPs. In contrast, a gradual increase in the zone of inhibition was recorded with increasing concentrations of

AgNPs. A negative control showed no inhibition zone revealed that there was no control. The positive control, carbendazim, showed an inhibition zone of 23 mm, which was comparable to the AgNPs concentration of 75 $\mu\text{g mL}^{-1}$ (T_5). The inhibition zone of 100 $\mu\text{g mL}^{-1}$ AgNPs (T_7) and the absence of inhibition in the negative control are presented in Fig. 4. The results demonstrate an increase in the zone of inhibition with higher concentrations of AgNPs, confirming their antifungal efficacy.

The result of the antifungal study against *A. flavus* aligns the reports of previous studies, using *Syzygium cumini* leaves mediated AgNPs (100 $\mu\text{g mL}^{-1}$) (21). Another study brought about 100 % inhibition using *Bacillus thuringiensis* MAE 6-mediated AgNPs (500 $\mu\text{g mL}^{-1}$), which showed an inhibition zone of 26 mm (22).

The AgNPs reduced the growth of *A. flavus* because it penetrates cell

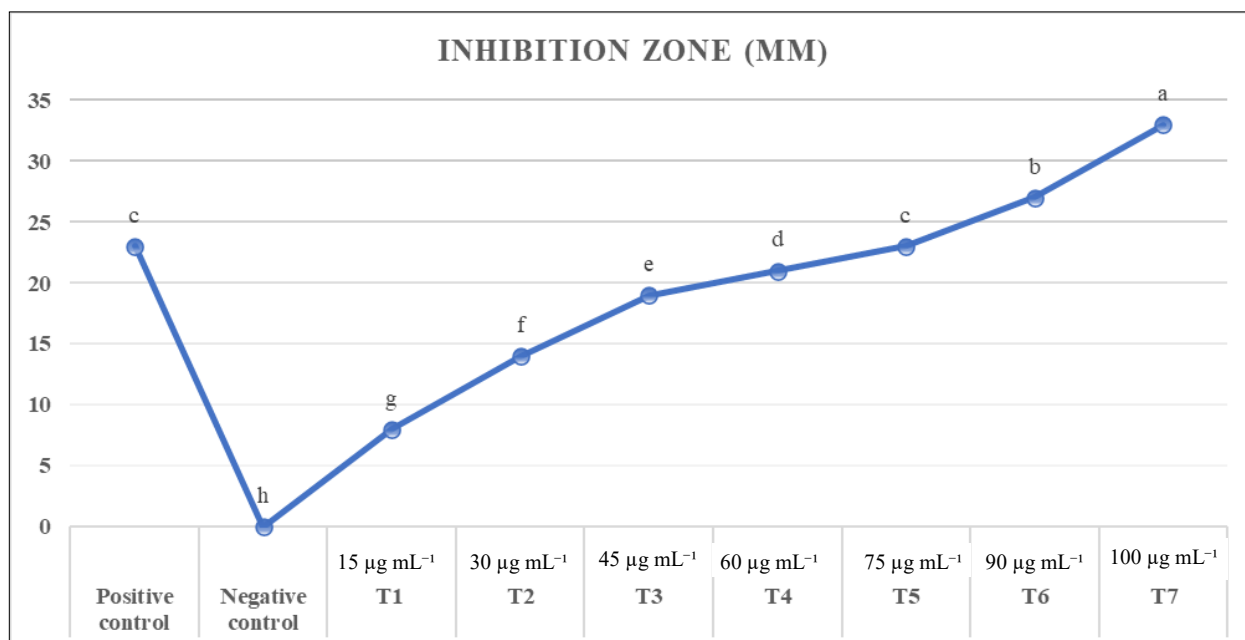


Fig. 3. Anti-fungal property of silver nanoparticles (AgNPs) against *Aspergillus flavus*.

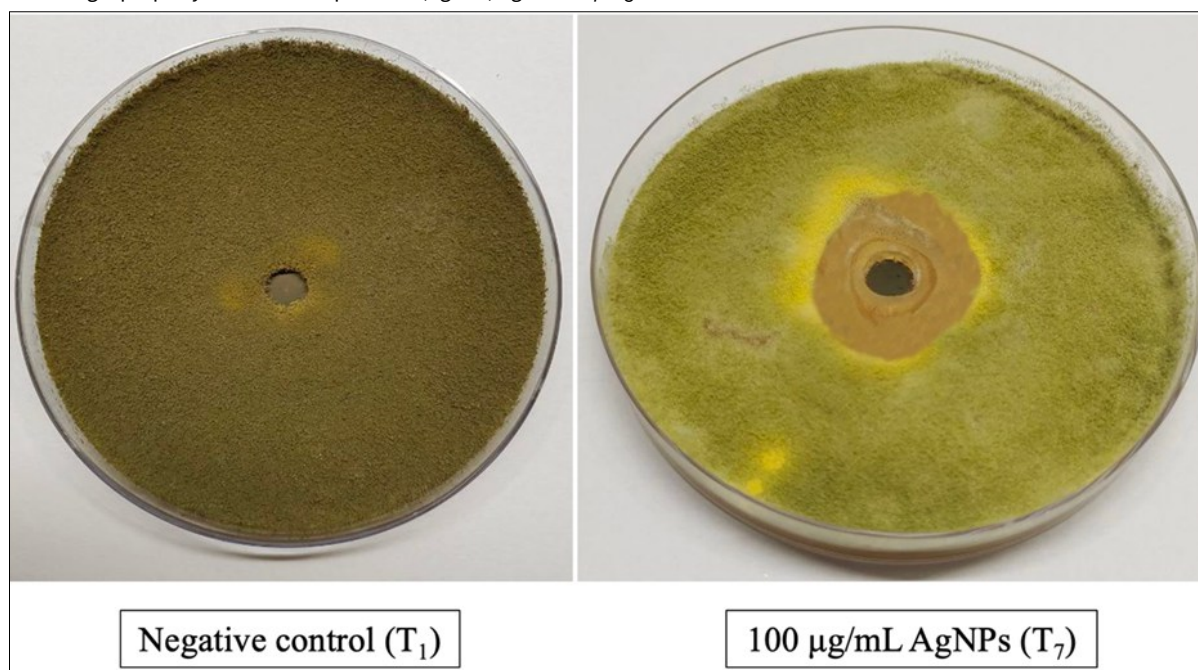


Fig. 4. *Aspergillus flavus* treated with distilled water (T₁) and 100 µg mL⁻¹ silver nanoparticles (AgNPs) (T₇).

wall of microbes due to their nano scale size and cause cell death by altering the cell membrane structure. The AgNPs perforates and denatures the membrane leading to rupture of microbial cell organelles. Silver ions released from AgNPs produce reactive oxygen species (ROS) inside the cell, which disturbs the DNA replication and cause membrane damage. The AgNPs also affect the transduction of bacterial signal, terminating cell multiplication and resulting in cell apoptosis. It also been reported that it interrupts adenosine triphosphate (ATP) production and denatures ribosomes (23). Silver ions affect the replicating nature of DNA, it inactivates the expression of ribosomal proteins, other cellular proteins and enzymes needed for ATP production (24). Our findings confirm and validate that the green synthesised AgNPs exhibit significant antimicrobial efficacy; moreover, AgNP-based coatings are promising agents against microbial contamination.

Influence of AgNPs with biopolymer coating on quality attributes of guava

Reducing and non-reducing sugars

Biopolymers with AgNPs coated fruits showed lower sugar content compared to uncoated fruits (Table 1). In these different coatings, treatment T₂ (Beeswax + AgNPs) showed low reducing sugar content of 4.21 % and 3.02 %, whereas the uncoated fruits showed 6.47 % and 6.29 % on the 8th and 12th days of storage respectively. A rapid increase in reducing sugars was observed up to 8th day after coating, after which it was observed to decline in all the treatments. The combination of biopolymer gelatin with AgNPs (T₃) also showed low reducing sugar level as 4.88 %, 4.77 % and 4.71 % on the 8th, 10th and 12th day of storage, respectively. In case of non- reducing sugars, the lowest was observed in T₂ (Beeswax + AgNPs) as 2.85 % and 2.65 % and the highest values were observed in control fruits as 4.42 % and 4.22 % on the 10th and 12th day of storage. (Gelatin + AgNPs) showed better results in non-

Table 1. Effect of biopolymers with silver nanoparticles (AgNPs) on reducing and non-reducing sugars in guava

Treatments	Reducing sugar (%)							Non-reducing sugar (%)						
	Storage intervals (Days)							Storage intervals (Days)						
	Initial day	2	4	6	8	10	12	Initial day	2	4	6	8	10	12
T ₁ (Control)	3.34	3.95	4.65 ^a	5.59 ^a	6.47 ^a	6.37 ^a	6.29 ^a	2.61 ^{ab}	2.79 ^a	3.27 ^a	3.73 ^a	4.07 ^a	4.42 ^a	4.22 ^a
T ₂ (Bee wax + AgNPs)	3.18	3.39	3.69 ^d	3.92 ^d	4.21 ^e	3.62 ^e	3.02 ^e	2.23 ^c	2.23 ^b	2.41 ^c	2.54 ^c	2.67 ^c	2.85 ^c	2.65 ^c
T ₃ (Gelatin + AgNPs)	3.32	3.73	4.06 ^c	4.51 ^c	4.88 ^d	4.77 ^d	4.71 ^d	2.73 ^a	2.88 ^a	3.03 ^b	3.18 ^b	3.36 ^b	3.56 ^b	3.34 ^b
T ₄ (Xanthan gum + AgNPs)	3.28	3.81	4.55 ^a	5.16 ^b	5.81 ^b	5.63 ^b	5.47 ^b	2.49 ^b	2.67 ^a	2.91 ^b	3.24 ^b	3.47 ^b	3.75 ^b	3.52 ^b
T ₅ (Guar gum + AgNPs)	3.34	3.84	4.32 ^b	5.05 ^b	5.18 ^c	5.09 ^c	4.99 ^c	2.79 ^a	2.89 ^a	3.07 ^{ab}	3.31 ^b	3.48 ^b	3.64 ^b	3.46 ^b
C.D (5 %)	NS	NS	0.168	0.503	0.314	0.309	0.318	0.276	0.267	0.259	0.204	0.169	0.273	0.299
SE(m)	0.067	0.063	0.048	0.142	0.090	0.090	0.090	0.077	0.077	0.074	0.056	0.048	0.077	0.087

reducing sugar level as 3.56 % and 3.34 % in the 10th and 12th day of storage. Here also, the overall non-reducing sugars increased up to the 10th day and thereafter started to decline in all treatments.

Guava fruits are categorised as climacteric fruit, because it first mature and then attain climacteric peak with peak production of ethylene coinciding with ripening. The conversion of starch into sugars is the final and crucial physiological process during fruit ripening, after which senescence sets in. Until the climacteric peak, sugars increased and after that a sudden decline was observed in both reducing and non-reducing sugars. The overall starch was completely utilised as sugars, after which no elevation in sugar levels were observed. In the later stages, the reduction in sugars is as a result of the consumption of these simple sugars during respiration, leading to their conversion into carbon dioxide and water (25).

Sugars not only provide texture and flavour but maintain nutritional value with improved preservation quality and shelf life of fruits. Apart from that, it acts as an osmo-protectant and mitigate chilling injury, which is a major problem in guava. Stress induced sugar conversion from starch also maintains the osmotic potential of cell, protects the membrane from damage, scavenging ROS, supply energy for the stress defense and reduces the damage caused by pathogens. Notably, Sucrose improves fruit size, nutritional characteristics, shelf life and consumer acceptance of the fruits (26). Reducing and non-reducing sugars are the carbohydrates which are differentiated based on chemical reactions. Reducing sugars having a free ketone or aldehyde group serve as a reducing agent, to reduce other molecules by donating electrons; but non-reducing sugars having ketal or acetal groups which are not oxidised. Fructose (5.6–7.7 %) and glucose (1.9 – 18.1 %) as a reducing sugar and sucrose (6.2–7.8 %) as a non-reducing sugar are the major sugars present in guava (27).

Grapes dipped with AgNPs solution at 30 ppm for 3 min showed low reducing sugars as 9.40 %, 9.65 % and 9.67 % in the 3rd, 6th and 9th day of storage. Dipping of fruits with AgNPs solution alone shown considerable changes in fruit sugars under postharvest condition (28). During the storage period, sugar accumulation increases with fruit ripening due to breakdown of starch into sugars. Rise in sugar level positively correlate with weight loss, ethylene emission, moisture loss and rate of respiration; negatively correlated with titratable acidity and fruit firmness. Biopolymer coating reduces the ethylene production and respiratory activity, thereby increasing the shelf life of fruits by delaying the climacteric peak and slowing down the ripening process (8). There are also reports that AgNPs have anti-ethylene potential, suppressing ethylene biosynthesis by releasing silver ions, inhibiting its action and interaction with ethylene receptors, thereby improving the storage life of fruits.

However, this part has not been taken up in the present study. Silver ion also delays the fruit senescence by eliminating several processes of aerobic respiration in Krebs cycle leads to leakage of intracellular ions; which impairs the respiratory electron transport system (29).

The role of biopolymer coating is also crucial for the improvement of quality attributes of guava and the present study emphasises the superiority of beeswax over the other treatments. Beeswax coating limits the oxygen diffusion and modifies the atmosphere inside the coating, which leads to lower oxidative metabolism and respiration. It lowers oxygen level, suppress the metabolic rate, starch to sugar conversion and decelerate the sugar consumption through respiration. Lower respiration rates naturally imply reduced utilisation of sugars, leading to their better preservation. Such coatings delay ripening processes including starch degradation sugar accumulation and changes in colour texture and firmness. Reduced respiration also results in lower organic acid metabolism since organic acids serve as major substrates for respiration (30).

Titratable acidity

Titratable Acidity (TA) is an indicator for the fruit shelf-life quality during storage and the gradual declination of TA was observed in all treatments as presented in Table 2. All the treatments showed similar level of TA during the initial day between 0.49 % and 0.51 %, which confirms the uniform selection of fruits at the start of the experiment. The control fruits (T₁) revealed continuous and rapid reduction in TA from 0.50 % (initial) to 0.32 % (12th day of storage), which indicates accelerated senescence in control fruits. In contrast, AgNPs incorporated biopolymer coatings retained higher TA throughout the storage. Among them T₂ (Beeswax + AgNPs) proved to be superior with values of 0.38 % at the 12th day of storage, followed by T₃ (Gelatin + AgNPs) coating as 0.36 % and T₄ (xanthan gum + AgNPs) and T₅ (Guar gum + AgNPs) recording same values of 0.34 %. Statistical analysis confirmed the significant differences among the treatments ($p \leq 0.05$) from the 6th day of storage.

Acidity retention is an important factor during postharvest preservation because it extends the storage life of fruits with inhibition of microbial growth. Organic acids like oxalic and citric acid reduces browning, spoilage and chilling injury; slow down ripening and maintains the fruit nutritional content and flavor. Preserved guava fruits with better titratable acidity content extended the marketable duration and diminished the post-harvest losses by slow down respiration, protects against pathogen attack and oxidative damage and delay senescence. Even, the exogenous application of oxalic acid reduced the chilling injury in guava fruits (31).

During fruit ripening, TA decreases due to the breakdown of

organic acids into sugars, particularly malic acid. Hence, there is an inverse relationship between TA and sugars during the period of fruit ripening (32). This can be explained from the reported work that biopolymer coating maintains the acidity level by restricting the oxygen-carbon dioxide movement inside the coating; avoid shriveling by arresting evaporation; and minimise the usage of organic acids by the limitation of aerobic metabolism (30).

Fruit decay

Decay percentage was very low during the initial period of storage after which it was observed to be rapid. Decay percentage increased gradually in all treatments during the period of storage, which indicates the natural deterioration process (Table 2). The control fruits (T_1) showed a steep rise in decay, from 20 % to 93.75 % in the 12th storage day, which confirmed the susceptibility of uncoated fruits to tissue breakdown and microbial spoilage. The application of AgNPs along with different biopolymers created a huge impact against the fruit decay. Among all treatments, T_2 (Beeswax + AgNPs) consistently reported low decay rate from 0 % to 63.75 % in the 12th day of storage. This was followed by guar gum + AgNPs (T_5) (68.75 %), gelatin + AgNPs (T_3) (72.5 %) and xanthan gum + AgNPs (T_4) (73.75 %) at the end of the storage period. The deterioration process was slow in fruits coated with AgNPs and different biopolymers, but it was rapid in control fruits.

The fastest decay rate occurs due to peak respiration, ethylene emission and transpiration. Continuous water loss of fruits makes the intracellular fluid more concentrated, which increases the ionic content and leads to cellular poisoning inside the cell. Water loss during preservation leads to stomata closure, loss of turgor pressure and metabolic disruption which results as wilting, tissue degradation, softening, shrinking, browning, loss in fruit texture, flavor and weight loss which accelerates senescence. These changes decline the fruit quality and market value (33).

The main reason for the decay reduction is because the fruits were coated with biopolymers and additionally, imbedded with antimicrobial efficacy proven AgNPs, proved good to reduce the microbial spoilage and limit the ethylene production (29). Biopolymer coating limits gaseous exchange, reduce the water loss through transpiration, slow down the metabolic process by reducing respiration and is also less prone to mechanical injury, because it forms a layer on the stomatal pores of fruit surface. Coated fruits maintain the firmness and other quality parameters for the long period due to tissue rigidity, reduced and delayed conversion of starch into sugars (34).

Apart from increasing the shelf life of fruits, these biopolymer coatings hold the AgNPs on the surface of fruits and favours the controlled release of silver ions. This immobilisation keeps the AgNPs evenly dispersed and active over periods of time. It forms an

antimicrobial layer that protects the fruit from microbial contamination and extends its shelf life, besides also enhancing the mechanical strength of the coating film (35). Beeswax is a reservoir of naturally occurring bioactive components such as fatty acids (10-hydroxy-trans-2-decenoic acid, cerotinic acid and palmitic acid), alcohols (triacontanol, hexacosanol, octacosanol and tetracosanol) and flavonoids (pinobanksin, chrysin, pinocembrin, tectochrysin and galangin) which have extensive antimicrobial and antioxidant property. In this study, Beeswax showed superior performance due to its low water vapor permeability and highly hydrophobic nature. It is composed of long-chain fatty acids, alcohols and esters, which form a highly non-polar structure. Beeswax forms a strong water-repellent barrier on the fruit surface, thereby limiting moisture loss, maintaining firmness and preserving higher tissue hydration. It also suppresses the respiration rate and delays ripening by restricting O_2 and CO_2 diffusion, compared to the hydrophilic hydrocolloids such as gelatin, xanthan gum and guar gum (36).

The study proves beyond doubt that biopolymer coating is a promising tool in post-harvest field; a lot of researches undergoes with the addition of nanometals and essential oils. Our study demonstrates that these novel coatings serve as a promising, eco-friendly and cost-effective technique to improve the storage life of fruits, especially guavas. The novelty of the study compared to the previous research on AgNP-based coatings is the differences in biopolymer combinations, formulation ratios and their effects on postharvest quality. This is highlighted to clearly demonstrate the originality of the work.

Additionally, the study was supported by characterisation of AgNPs. The UV-Visible absorption spectrum revealed a distinct absorption band centred at 460 nm, indicating the characteristic surface plasmon resonance of silver nanoparticles. Furthermore, SEM analysis showed mildly agglomerated spherical particles. XRD analysis confirmed the crystalline nature of the synthesised nanoparticles, with sharp diffraction peaks observed at 38.20° , 32.30° and 46.20° . The stability of the material was confirmed by a zeta potential value of -4.02 mV. Overall, the characterisation results demonstrated the successful formation of AgNPs with the desired properties (9).

Conclusion

The shorter shelf life of fruits presents a significant challenge during storage, leading to substantial waste and loss caused by inadequate postharvest handling facilities and microbial contamination. Biopolymers offer a promising solution for food coatings because of their renewability, biodegradable nature and ability to enhance food quality and safety. They provide a sustainable alternative to synthetic coatings by reducing

Table 2. Effect of biopolymers with silver nanoparticles (AgNPs) on titratable acidity and decay rate in guava

Treatments	Titratable acidity (%)							Decay (%)					
	Storage intervals (Days)							Storage intervals (Days)					
	Initial day	2	4	6	8	10	12	2	4	6	8	10	12
T ₁ (Control)	0.50	0.47	0.43	0.39 ^b	0.37 ^b	0.34 ^d	0.32 ^d	20	41.25 ^a	71.25 ^a	81.25 ^a	88.75 ^a	93.75 ^a
T ₂ (Bee wax + AgNPs)	0.50	0.49	0.46	0.44 ^a	0.41 ^a	0.4 ^a	0.38 ^a	0	11.25 ^b	18.7 ^c	33.75 ^c	42.5 ^c	63.75 ^d
T ₃ (Gelatin + AgNPs)	0.49	0.46	0.44	0.43 ^a	0.41 ^a	0.38 ^b	0.36 ^b	0	12.5 ^b	22.5 ^c	32.5 ^c	50 ^b	72.5b ^c
T ₄ (Xanthan gum + AgNPs)	0.51	0.49	0.47	0.43 ^a	0.38 ^b	0.36 ^c	0.34 ^c	0	12.5 ^b	27.5 ^b	40 ^b	51.25 ^b	73.75 ^b
T ₅ (Guar gum + AgNPs)	0.51	0.48	0.46	0.43 ^a	0.39 ^{ab}	0.36 ^c	0.34 ^c	0	11.25 ^b	22.5 ^c	33.75 ^c	51.25 ^b	68.75 ^c
C.D (5%)	NS	NS	NS	0.02	0.026	0.022	0.022	NS	4.206	5.006	3.54	5.287	3.927
SE(m)	0.008	0.01	0.008	0.006	0.008	0.006	0.006	-	1.33	1.646	1.164	1.738	1.291

environmental hazards while meeting consumer demand for healthier and natural food choices. Our novel combination of coatings for guava fruits improves the shelf-life along with quality parameters for extended period of storage. The potential use of metallic nanoparticles such as silver nanoparticles in extending the shelf life of fruits is proven but one critical part to be addressed is the threshold residual level or persistence in the fruit which is a major research gap which warrants immediate attention and is an *a priori* demand in this aspect. Our findings open the gates and create the pathway for the further line of research such as optimisation of nanoparticle concentration and size, exploration of bioactive nanomaterials, development of safe, scalable and consumer acceptable nano-coatings for preservation of guavas and other fruits. We acknowledge that the use of AgNPs in food applications raises concerns regarding nanoparticle migration, long-term exposure and regulatory compliance. Another wanting area is validation initially on small animals and further clinical studies which are absolutely necessary. The AgNPs release kinetics, toxicity and regulatory studies of nanomaterials in fruits and antimicrobial study on microbes relevant to guava spoilage during storage and transportation are the knowledge gaps still not come to light.

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Authors' contributions

SRJA and BSM designed the framework and concept of the study under the supervision of SK. BM developed the methodology for the antimicrobial study. PV contributed to the development of analytical tools and assisted with data interpretation. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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