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Research Article

Enhancing shelf-life of Mango (*Mangifera indica* L.) using biopolymer-based silver nanoparticle coatings

Krishna Prasanth Y*
Division of Horticulture, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India
Sajan Kurien
Division of Horticulture, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India
Madhumitha B
Division of Plant Pathology, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India
Ramesh Kumar P
Division of Crop physiology and Biochemistry, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India
Vijayakumar R M
Division of Horticulture, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India
Giriprasath R S
Division of Horticulture, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India
Bharanidharan A
Division of Horticulture, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu - 641114, India

*Corresponding author. E-mail: krishnaprasanthphd@gmail.com

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Abstract
Mango fruits harvested at the right maturity ripen quickly but have a short shelf life, are prone to moisture loss, and are susceptible to microbial spoilage, resulting in severe post-harvest losses. This experiment was undertaken with the major objectives of increasing shelf life while maintaining quality. The study focuses on the green synthesis of silver nanoparticles (AgNPs) incorporated with different biopolymers (beeswax, arabic gum, chitosan, and guar gum), which formed the treatments, using the dip-coating method in two mango varieties, namely Alphonso and Bangalora. The AgNPs were green-synthesised using *Sauropus androgynus* (Chekkurmanis) leaf extracts and further characterised using Scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) to confirm the presence of the nanomaterial. The coated fruits were stored at ambient room temperature, and their physiological and biochemical attributes were systematically monitored throughout the storage period which extended up to 16 days. The results revealed that postharvest treatments with beeswax (20% v/v) incorporated with AgNPS showed the most promising effects, extending shelf life to 16.72 days (Alphonso) and 18.86 days (Bangalora), compared to 12.8 days in uncoated fruits. This treatment also significantly reduced physiological weight loss (12%), maintained higher firmness (up to 14.43 N), and delayed increases in total soluble solids, sugars, and carotenoids. This research highlights the potential use of *S. androgynus* mediated AgNP-based biopolymer coatings as a sustainable postharvest method to prolong the shelf life of mangoes, making this the first report on mangoes with retention of fruit quality under ambient storage.

Keywords: Biopolymer, Green synthesis, Nanoparticles, Postharvest, Shelf-life

INTRODUCTION

Mango (*Mangifera indica* L.,) is referred to as the ‘King of fruits’ because of its delicious flavor and taste. The crop is rich in nutrients, protein, vitamins A and C, minerals such as potassium, magnesium, calcium, sodium, iron, and manganese (Pérez-Meza *et al.,* 2024). India is the leading producer of mangoes globally, contributing to more than half of the total global production (De and Dey, 2025). The annual production of mangoes is approximately 20.77 million tonnes from a cultivated area of 2.35 million hectares (Mishra *et al.,* 2024). Mango is a climacteric fruit characterized by rapid ripening and a limited shelf life. Its ripening is characterised by, softening of texture, conversion of starch into sugars and moisture loss. Though India is the leading producer of mangoes, exports are comparatively low due to the fruit's highly perishable nature and inadequate post-harvest infrastructure and techniques. This also makes it more vulnerable to postharvest disease infection, thereby reducing export quality (Singh *et al.,* 2024a). Several post-harvest technologies are used to increase shelf-life by inhibiting metabolic activity, including chemical and non-chemical treatments. Post harvest treatments like modified atmosphere storage (Perumal *et al.,* 2021; Thakur *et al.,* 2022), controlled atmosphere storage (Bender *et al.,* 2021), chemical treatments including 1-Methylcyclopropene (Yuan *et al.,* 2023; Hasan *et al.,* 2024), ozone treatment (Bambalele *et al.,* 2023), Nitric oxide (Ren *et al.,* 2020) and edible coating (Tavassoli-Kafrani *et al.,* 2022) has been shown to be promising for enhancing shelf life.

Edible coatings form a thin layer of protection on the fruit's surface and serve as sustainable postharvest treatments. It acts as a barrier that regulates oxygen exchange, controls moisture loss, and minimizes solute movement within the fruit (Bambalele *et al.,* 2021). Edible coatings such as chitosan (Parvin *et al.,* 2023), arabic gum (Gill *et al.,* 2024), xanthan gum (Kumar *et al.,* 2023), Guar gum (Qambrani *et al.,* 2022), and beeswax (Sousa *et al.,* 2021) have been used for regulating the ripening process in mango. A key benefit of edible coatings is that their natural composition is often enriched with antioxidants and vitamins, which are beneficial and promote consumer health. Additionally, they exhibit anti-browning and antimicrobial properties, thereby preserving fruit quality during storage (Tavassoli-Kafrani *et al.,* 2022).

Nanotechnology offers an innovative approach to extending the shelf life of fresh fruit through nanoparticle-incorporated edible coatings. This advanced preservation technique enhances the antimicrobial, antifungal, and antiviral properties of edible coatings while minimising exposure to and absorption of nanomaterials. Further, the incorporation of nanoparticles have been reported to improve the overall efficiency and cost-effectiveness of these protective edible coatings. Several nanoparticles, such as silver, zinc oxide, and titanium dioxide, have been shown to possess high antimicrobial activity and are also stable (Odetayo *et al.,* 2022).

Green-synthesized silver nanoparticles (AgNPs), produced using natural plant extracts or other organic materials, serve as reducing agents, offering itself as an eco-friendly and sustainable alternative. When combined with biopolymers, they create a superior coating material with enhanced protective properties, making them very effective in prolonging the shelf-life. Some reported applications of AgNPs-based coatings include the using carboxymethyl cellulose (CMC) and guar gum -based AgNPs nanoparticles on mangoes allowing them to be stored at 13° C for up to four weeks (Hmmam *et al.,* 2021); adding AgNPs to a sodium alginate film to coat bananas resulted in little weight loss and a notable decrease in total bacterial colonies, which significantly increased their shelf life (Zhang *et al.,* 2024); and the application of starch-based coatings embedded with AgNPs on strawberries, extending shelf life by 2–6 days at ambient temperature and 8–16 days under cold storage conditions (Taha *et al.,* 2022).

Based on the gap analysis of the existing literature, it can be inferred that only a limited number of studies have focused on the use of edible, nutritionally rich medicinal plants as reducing and stabilising agents for AgNP synthesis in postharvest fruit coatings. This study was therefore designed to explore *Sauropus androgynus* as a novel, food-compatible bioresource for developing nano-based biopolymer coatings. *Sauropus androgynus*, is also known as the 21st-century vegetable and multivitamin plant (Aruna *et al.,* 2022). Besides, the extract has been shown to be rich in alkaloids, flavonoids, tannins, terpenoids and phenolic compounds (Abhimannue *et al.,* 2021).

The present research focused on the green synthesis and characterisation of AgNPs using the *Sauropus androgynus* plant extract to develop a novel nanobased biopolymer coating to enhance the storage stability and quality attributes of mango fruits.

MATERIALS AND METHODS

Mango variety

The study was conducted in 2024 at the Horticulture Laboratory of the School of Agricultural Sciences at Karunya Institute of Technology and Sciences, Coimbatore. The two commercial mango varieties (Alphonso and Bangalora) used in the study, were procured from the local market in Coimbatore, Tamil Nadu. The procured fruits were fresh uniform in size, at the fully mature green stage, free from pests and diseases, and without any visible symptoms of disease or physical damage.

Preparation of aqueous extract using chekurmanis

Fresh chekurmanis (*Sauropus androgynus* L.) also known as a multivitamin plant, were collected from Karunya Medicinal Garden and further authenticated at the Botanical Survey of India, Coimbatore. Leaves were initially cleaned under running water to remove surface contaminants. The cleaned leaves were left in the shade and air-dried to protect their phytochemical integrity before being ground into a fine powder. To prepare the plant extract, 5 g of powdered leaves were combined with 100 mL of deionised water in an Erlenmeyer flask. The mixture was heated to 80°C for 90 minutes and was constantly stirred. After this procedure, the solid residues were removed from the solution by filtering through Whatman No. 1 filter paper. For use in later experimental processes, the resultant filtrate was then refrigerated at 4°C.

The nanoparticle was synthesized by mixing the aqueous leaf extract of Chekurmanis with the 1mM silver nitrate solution at a ratio of 1:9 volume/volume ratio (Extract : $AgNO_3$) (Bhavi *et al.,* 2025). In the case of *Sauropus* extract and $AgNO_3$ the mixture used was 1:9, selected based on the available literature.The mixture was placed in a water bath and maintained at 80°C for 45 minutes. The change in colour from pale yellow to brown indicated a decrease in silver content. Further, to this, the mixture was centrifuged for 30 minutes at 3000 rpm.To get rid of any excess silver ions, the precipitate that was left behind and contained AgNPs was cleaned twice with distilled water. Finally, the precipitate was lyophilised (freeze-dried) to powder. The procedure is given as a flowchart (Fig. 1).

Characterization of silver nanoparticles

The characterization of green-synthesized AgNPs was analysed using several methods. The size and shape of the nanoparticles determined by Scanning Electron Microscopy (SEM) using a JSM-6390 SEM, which also revealed detailed surface characteristics. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify the functional groups in the plant extracts responsible for converting Ag□ ions into elemental silver (Ag^0) and for the subsequent stability of the nanoparticles, which act as natural capping agents that prevent aggregation. The hydrodynamic diameter and polydispersity index (PDI) of AgNPs were determined by Dynamic Light Scattering (DLS), which was used to assess colloidal stability and particle size distribution in suspension.

Preparation of edible Nano-coating biopolymer

The green synthesised AgNPs were coated on mango fruits using different biopolymers, such as arabic gum, guar gum, beeswax, and chitosan, all of food-grade quality. Arabic gum biopolymer was prepared by dissolving 10% (w/v) finely ground Arabic gum powder in distilled water at 40°C for 15 minutes. Subsequently, the solution was cooled down to a temperature of 20°C. Once the coating solution cooled, 1% glycerol was added as a plasticizer to increase its strength and flexibility (Saleem *et al.,* 2020). For guar gum, a 2% (w/v) solution was prepared by mixing 2g of guar gum powder in 100 mL of distilled water (Hmmam *et al.,* 2021). For the 20% (v/v) biopolymer, it was melted to a liquid state by heating for 5 minutes at 75 °C. Then, 20 ml of the beeswax was mixed with 80 ml of coconut oil using a magnetic stirrer to make it homogenous (Nasrin *et al.,* 2020). The chitosan biopolymer was prepared by dissolving 20g chitosan in 10 ml of glacial acetic acid, which was then dissolved in 1 litre of water. The solution's pH was adjusted to 5.6 using NaOH. 1 mL of Tween 20 was also added to increase wettability (Zhu *et al.,* 2008).

The lyophilised AgNPs obtained after freeze-drying were resuspended by weighing the AgNP powder and dissolving it in deionised water to prepare a 100 ppm AgNP stock solution. The suspension was vortexed for 2–3 minutes and ultrasonicated for 15 minutes to achieve complete and uniform nanoparticle dispersion. This 100 ppm stock solution was then added to each biopolymer solution at a 1:9 (v/v) ratio, resulting in a final AgNPs concentration of 10 ppm in all coating formulations. After preparing the biopolymer solution, the AgNPs solution was added dropwise using a burette and stirred on a magnetic stirrer at a 1:9 ratio to ensure uniform distribution. The technique used for fruit coating was the dip method, applied to paper plates. The fruits were stored under ambient laboratory conditions at a temperature of (26 ± 2 °C) with a relative humidity of (65–75%), which was monitored on a daily basis throughout the 16-day storage period.

Quality parameters

Shelflife

Fruit shelf life was determined as the number of days from the treatment initiation until 50% of the fruits exhibited visible shrivelling. To minimise subjectivity and enhance consistency and precision, a quantitative visual grading system was employed to evaluate shrivelling. A standardized visual scale with a range of 0 to 5 was used to evaluate shrivelling based on the percentage of surface wrinkles, where 0 = no wrinkling, 1 = slight wrinkling (<10% surface area), 2 = visible wrinkling (10 - 25%), 3 = moderate wrinkling (25 - 50%), 4 = severe wrinkling (50 - 75%), and 5 = extreme shrivelling with pronounced dehydration.

Physiological loss in weight (PLW) (%)

Initial weight and weight at different stages of the fruits were measured at fixed intervals

PLW (%) = Initial weight (g) – final weight (g) /Initial weight (g)

Fruit firmness (N)

Fruit firmness was measured at different stages with a fruit penetrometer (Nunes) using an 8mm probe at 4-day intervals and expressed in Newtons.

Total soluble solids (°Brix)

The TSS content of fruits was measured using a hand digital refractometer (Milwaukee).

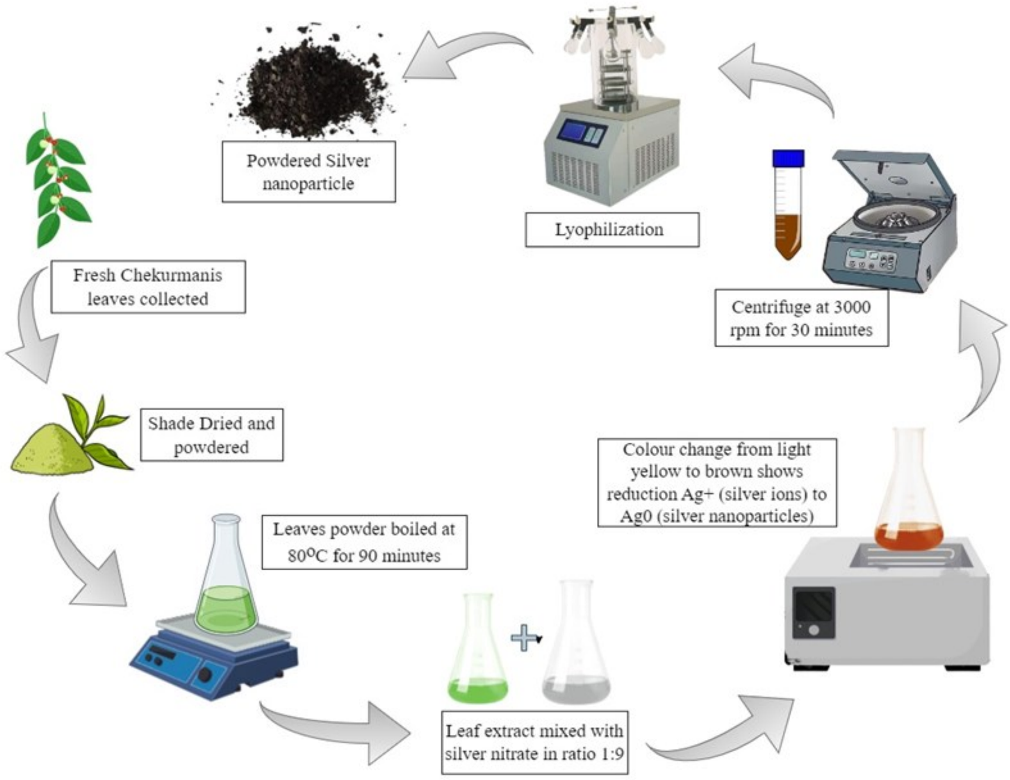

Fig. 1. *Green synthesis of silver nanoparticles using Chekurmanis (Sauropus androgynus) leaf extract: The step-by-step process*

Total sugars

Total sugars content of fruits was analysed by colorimetric method suggested by Hedge and Hofreiter, (1962)

Total carotenoids

The carotenoid was estimated by homogenizing 0.25 g of fruit pulp in 20 mL of 80% acetone (v/v). Filtered extracts were used to measure absorbance with a UV/Vis spectrophotometer at 480 and 510 nm, as suggested by Jensen, (1978) and calculated by following the formula and unit of expression is µg g^{-1}

$$Carotenoids = 7.6\,(OD\,480nm) - 1.49\,(OD\,510\,nm) \times \frac{V}{1000} \times (W)$$

where *OD* = optical density, *V* = final volume of 80% acetone, and *W* = sample weight

Statistical analysis

The experiment was carried out in a factorial completely randomized design (FCRD) with three replications, Each replication per treatment per variety consisted of 10 fruits. The treatments were five with three replicates, the sample size per treatment was therefore (n = 30) fruits. Since five treatments were applied to each variety, the total number of fruits used per variety was 150, and 300 for the entire experiment. The data were statistically analysed using Analysis of Variance (ANOVA) to assess significant differences and ensure the reliability of the results. Factor A – Mango varieties Alphonso and Bangalora, Factor B – included the four different biopolymer coating and a control of untreated fruits (i.e., no dipping in water or biopolymer solutions).The treatment combinations in the study were Control, Arabic Gum + AgNPs, Guar Gum + AgNPs, Beeswax + AgNPs, and Chitosan + AgNPs. Data analysis was conducted at 4-day intervals throughout the coating process, extending to the 16th day to monitor changes over time. The mean comparison was carried out using the Least Significant Difference test (LSD), which revealed differences among treatments within the same day of storage but not across different storage periods. Differences among treatment means were considered significant at $p \leq 0.05$, as indicated by different superscript letters has been added as footnote in the tables. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS).

RESULT AND DISCUSSION

Characterization of silver nanoparticles

Fourier Transform Infrared Spectroscopy (FTIR) Spectroscopy

The FTIR analysis shows that different phytochemicals are involved in the green synthesis process by comparing the functional groups found in the powdered leaf extract with the green-synthesized AgNPs shown in Fig. 2. In both spectra, a broad peak around 3441.01 cm^{-1} in the leaf extract and 3419.79 cm^{-1} in AgNPs corresponds to O–H or N–H stretching vibrations, indicating the presence of alcohols, phenols, or amine groups. The peak observed at 1743.65 cm^{-1} in the leaf extract spectrum and assigned to C=O stretching in esters or aldehydes disappears after nanoparticle synthesis, suggesting that these groups may have undergone oxidation or some form of transformation during the reduction of Ag^+. Furthermore, the peak at 1111.00 cm^{-1} in the spectrum, corresponding to C–N stretching, disappears in the AgNP spectrum, suggesting a potential role in stabilising or capping the nanoparticles. The C=O or aromatic C=C stretching band shift from 1629.85 cm^{-1} in the leaf extract to 1637.56 cm^{-1} in AgNPs provides more evidence that carbonyl or amide groups interact with the surface of the nanoparticle Also, a small shift occurred from 1419.61 to 1400.32 cm^{-1}, which corresponds either to the C–H bending vibration or vibrations of the COO^- groups and indicating that these groups may contribute to nanoparticle stabilization. Overall, the spectral differences confirm the involvement of hydroxyl, carbonyl, and ether or amine groups in the bioreduction and stabilization of AgNPs, validating the successful green synthesis using bioactive compounds from the leaf extract.

Scanning Electron Microscopy (SEM) analysis

The morphology of the AgNPs studied using SEM analysis at magnifications of 2700x and 700x, revealed a rough, agglomerated, and non-uniform distribution of nanoparticles, confirming the effective capping of AgNPs by bio-compounds present in the extract (Fig. 3). Recent studies have highlighted the significance of phytochemicals such flavonoids, tannins, saponins, and polyphenols in the decrease and stabilization of nanoparticles during green synthesis (Ritu *et al.,* 2023). In the case of *Sauropus* extract and $AgNO_3$ the mixture used was in the ratio of 1:9 and the ratio was selected based on the available literature. This was the only one combination used in the present study and hence the difference in characterisation was not rationale. The particle size also differed due to agglomeration, as shown in Fig. 3. Agglomeration of AgNPs in the green synthesis is a common problem and can occur for several physicochemical reasons. One of the primary factors is AgNPs high surface energy, which can lead the particles to group together to reduce their surface area (Restrepo and Villa, 2021). Additionally, the lack of effective capping or stabilizing agents during green synthesis can lead to particle agglomeration (Min *et al.,* 2023). Furthermore, environmental factors including temperature, ionic strength, and pH, may cause agglomeration by influencing the zeta potential of nanoparticles and their colloidal stability (Sati *et al.,* 2025). Therefore, to minimise agglomeration and produce monodispersed AgNPs in green synthesis processes, it is crucial to optimise synthesis conditions, use effective stabilising agents, and control environmental conditions.

Energy-dispersive X-ray (EDX) analysis

As seen in Fig. 4, the AgNPs Energy Dispersive X-ray (EDX) profile displayed strong signals that corresponded to silver atoms. The reduction of Ag ions with the

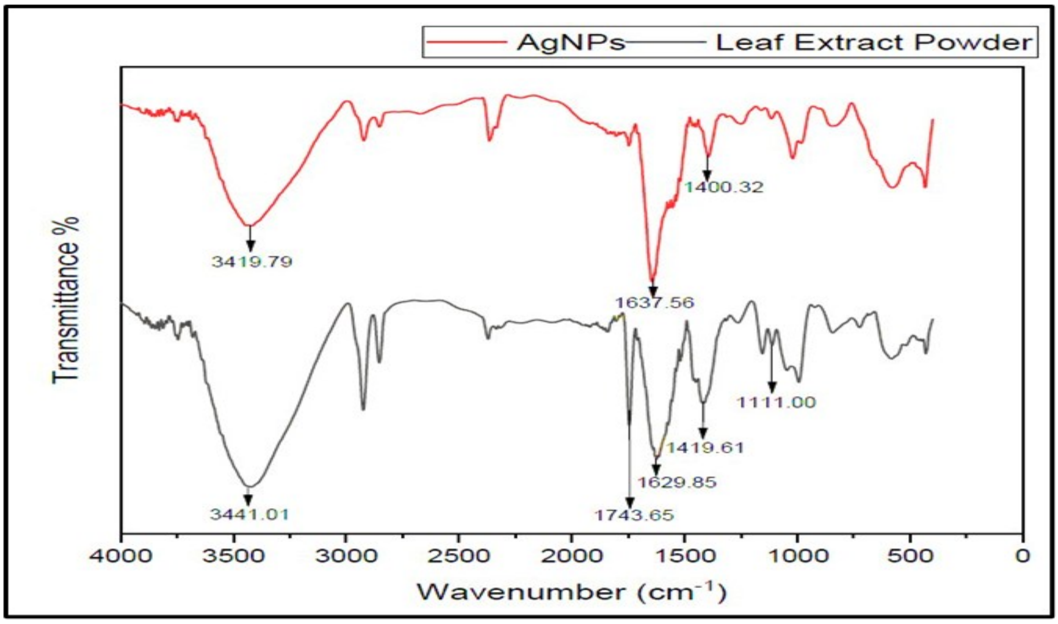

Fig. 2. *Fourier transform infrared spectroscopy (FTIR) analysis of chekurmanis (Sauropus androgynus) leaf extract powder and biosynthesized silver nanoparticles (AgNPs) showing changes in functional groups involved in reduction and capping of AgNPs*

chekurmanis leaf extract yields crystalline AgNPs, as evidenced by the EDX pattern. The presence of AgNPs was confirmed by EDX analysis, which showed prominent energy peaks for silver atoms between 2–4 keV. Our results were similar to those obtained by Ghasemi *et al.* (2024), who synthesised AgNPs using an aqueous extract of *Rubus discolour* leaves and demonstrated that a significant silver peak occurred at 3.0 keV.

Particle size analysis

The measured mean particle size was 92.56 r.nm, with the most significant concentration at 137.2 nm and a maximum intensity. Additionally, the sample exhibited a polydispersity index (PDI) value of 0.296, indicating a relatively uniform particle size distribution. These findings are illustrated in Fig. 5.

Shelf-life (days)

The data presented in Table 1 clearly demonstrate that the application of AgNP-incorporated biopolymer coatings significantly extends the shelf life of both Alphonso and Bangalora mango varieties. Among the treatments, Beeswax coating was the most effective in extending shelf life, with mean values of 16.72 days in Alphonso and 18.86 days in Bangalora, indicating its superior ability to reduce moisture levels and extend shelf life, as shown in Fig. 6.

The positive impact of beeswax coatings can be attributed to their ability to form a hydrophobic layer, reducing transpiration and minimising oxygen permeability, thereby slowing metabolic processes. Its take-up feasibility is high, as it is a locally available resource. This finding is in line with the report by Trinh *et al.* (2022), who noted that beeswax-based coatings combined with nanomaterials effectively reduced ethylene production and respiration rates, thereby extending the shelf life of fresh bananas, strawberries, and fresh-cut apples.

In contrast, fruits without coatings had a shorter shelf life. (12.70 days in Alphonso and 12.81 days in Bangalora). This confirms that the lack of protective coatings causes faster deterioration and increased metabolic activity and also, aligns with results obtained in the studies of Hmmam *et al.* (2021) and Basumatary *et al.* (2022), who in their study emphasized that untreated fruits are prone to rapid moisture loss, softening, and microbial spoilage. There are large number of articles which have dwelled on this antimicrobial activity of AgNPs aspect and proved beyond doubt (Loo *et al.,* 2018; Odetayo *et al.,* 2022; Wasilewska *et al.,* 2023) It is an accepted fact that climacteric fruits ripen after harvest produce ethylene and a surge observed in the respiration rate. The nanoparticles particularly Silver and Lead, have the capacity and distinct properties to delay fruit ripening (Odetayo *et al.,* 2022). However, in the present study, this aspect was not taken up separately, as it is a well-established concept.

Arabic Gum coating treatment was also effective, with enhanced shelf-life values reaching 15.80 days and 16.26% days in Alphonso and Bangalora, respectively. Arabic Gum's film-forming properties provide a protective coating that reduces water vapour loss and maintains fruit firmness, a conclusion consistent with the findings of Basumatary *et al.* (2022). Similarly, Guar Gum coatings demonstrated a moderate impact, resulting in shelf-life values of 15.03 days (Alphonso) and 15.23 days (Bangalora), Similar outcomes were also noted by Hmmam *et al.* (2021), who reported that AgNPs derived from guar gum efficiently decreased microbial decay and increased the mango shelf life.

Interestingly, chitosan coatings had a balanced effect, improving shelf life to 13.63 days in Alphonso and

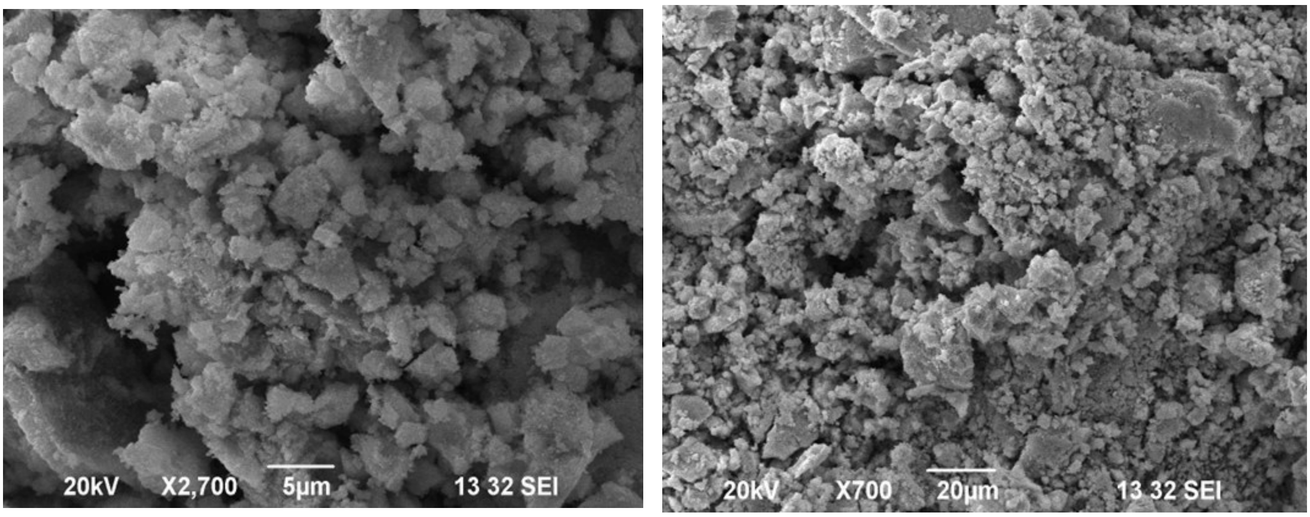

Fig. 3. *Scanning electron microscopy (SEM) micrographs of chekurmanis (Sauropus androgynus) leaf extract-mediated silver nanoparticles (AgNPs): (a) higher magnification (×2700) showing finer aggregated particles, and (b) lower magnification (×700) showing broader agglomerated clusters.*

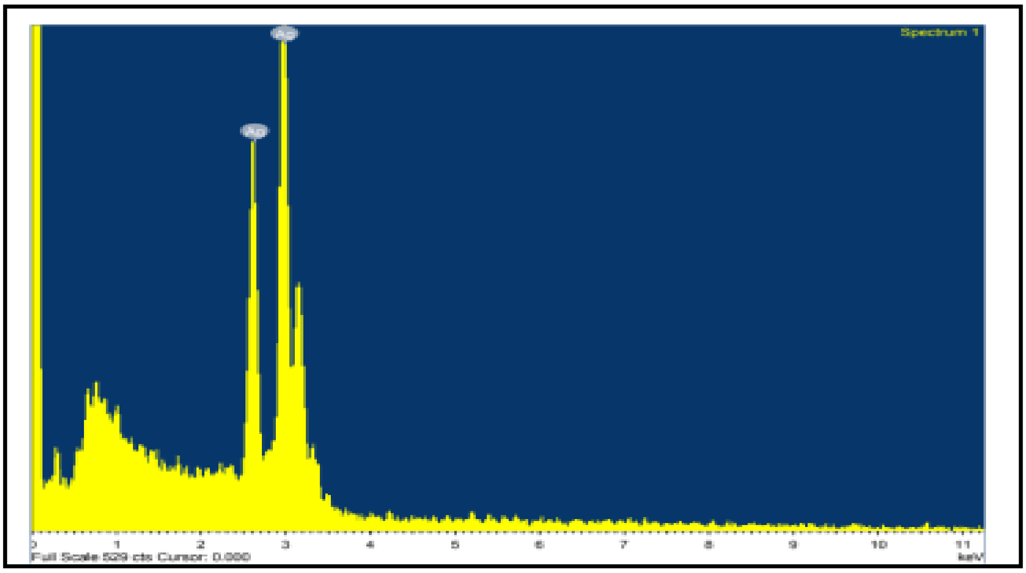

Fig. 4. *Energy-dispersive X-ray (EDX) spectrum of green-synthesized silver nanoparticles (AgNPs) confirming the presence of elemental silver as the major component*

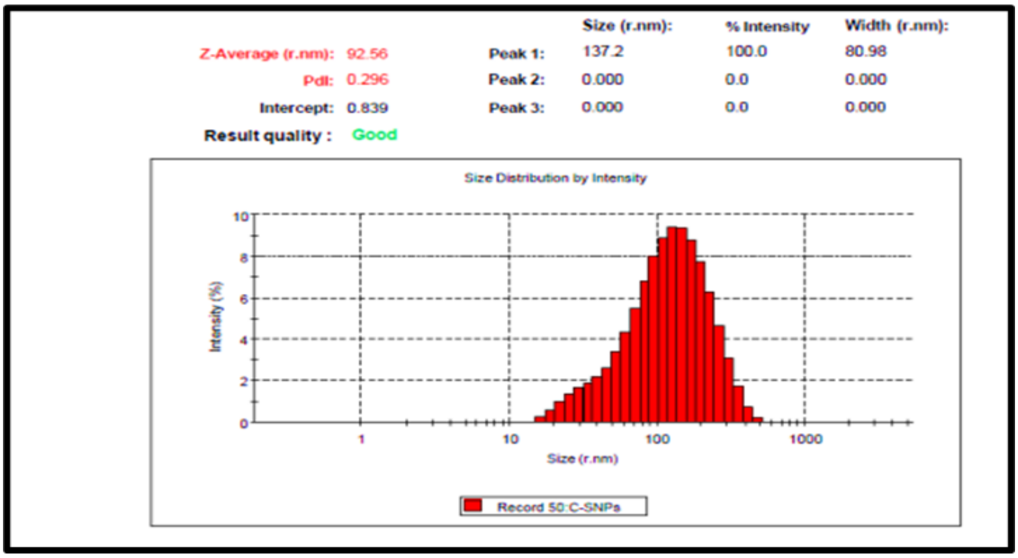

Fig. 5. *Dynamic light scattering (DLS) size distribution by intensity of green-synthesized silver nanoparticles (AgNPs), showing a Z-average hydrodynamic diameter of about 92 nm with moderate polydispersity.*

14.41 days in Bangalora. According to Singh *et al.* (2024b), chitosan's antibacterial properties and capacity to alter the internal gaseous composition are important for delaying fungal infections and reducing oxidative stress during storage. Overall, the results suggest that the prospective capabilites of Beeswax and Arabic Gum coatings, particularly those incorporating AgNPs, are most effective in extending mango shelf life. The enhanced performance of AgNPs in coatings is attributed to their antimicrobial activity, ability to maintain fruit firmness, and capacity to form a semi-permeable film that balances internal gaseous exchange and moisture retention (Singh *et al.,* 2024b).

Physiological loss in weight (PLW) (%)

The PLW% of Alphonso and Bangalora mango varieties after 16 days of storage was affected greatly by the use of different biopolymer coatings (Table 2). The highest weight loss during storage was observed in the uncoated fruits of both varieties, with 15.28% for Alphonso and 14.53% for Bangalora on day 16, which again indicated the high moisture resulting from increased respiration and transpiration rates. The same findings have also been reported by Hmmam *et al.* (2021), who found higher PLW% loss in uncoated mango fruits when stored for prolonged periods. The use of Beeswax coating with AgNPs significantly reduced weight loss to 12.17% for Alphonso and 12.74% for Bangalora, indicating its functional properties as an excellent barrier that minimises moisture loss by creating a semi-permeable layer on the fruit surface (Eshetu *et al.,* 2019). All treatments using AgNP-incorporated biopolymer coatings effectively reduced PLW by providing a good barrier to moisture loss and respiratory gas-

Table 1. Effect of different biopolymer coatings with AgNPs on the shelf life of mango varieties

Treatments		Mean (Days)
Varieties	**Biopolymer**	
Alphonso	Control (untreated)	12.70^{f}
Alphonso	Arabic gum + AgNPs	15.80^{bc}
Alphonso	Guar gum + AgNPs	15.03^{cd}
Alphonso	Chitosan+ AgNPs	13.63^{ef}
Alphonso	Beeswax+ AgNPs	16.72^{b}
Bangalora	Control (untreated)	12.81^{f}
Bangalora	Arabic gum + AgNPs	16.26^{b}
Bangalora	Guar gum + AgNPs	15.23^{cd}
Bangalora	Chitosan+ AgNPs	14.41^{de}
Bangalora	Beeswax+ AgNPs	18.86^{a}
CD 5%		1.018
SE (d)		0.488

Values followed by different superscript letters within the same column differ significantly according to the Least Significant Difference (LSD) test at $p \leq 0.05$. Superscript letters indicate comparisons among treatments within the same storage period

Table 2. Effect of different biopolymer coatings with AgNPs on the physiological loss in weight (%) of mango varieties

Treatments		Day of Storage			
Varieties	**Bio-polymer with AgNPS**	**4 days**	**8 days**	**12 days**	**16 days**
Alphonso	Control (untreated)	3.64^{a}	6.58^{a}	11.09^{bc}	15.28^{a}
Alphonso	Arabic gum + AgNPs	3.62^{ab}	6.45^{a}	10.17^{f}	13.04^{de}
Alphonso	Guar gum + AgNPs	3.55^{abc}	5.36^{a}	10.92^{cd}	12.70^{ef}
Alphonso	Chitosan+ AgNPs	3.35^{cd}	6.43^{d}	11.34^{ab}	14.16^{bc}
Alphonso	Beeswax+ AgNPs	2.51^{e}	6.31^{ab}	9.87^{g}	12.177^{f}
Bangalora	Control (untreated)	3.42^{abcd}	5.92^{bc}	11.53^{a}	14.53^{abc}
Bangalora	Arabic gum + AgNPs	3.26^{d}	5.38^{d}	10.69^{f}	13.77^{cd}
Bangalora	Guar gum + AgNPs	3.37^{bcd}	5.62^{cd}	11.05^{cd}	13.85^{bcd}
Bangalora	Chitosan+ AgNPs	3.49^{abcd}	5.65^{cd}	11.36^{ab}	14.66^{ab}
Bangalora	Beeswax+ AgNPs	3.27^{d}	5.38^{d}	10.47^{e}	12.74^{ef}
CD 5%		0.256	0.393	0.266	0.856
SE(d)		0.123	0.188	0.127	0.41

Values followed by different superscript letters within the same column differ significantly according to the Least Significant Difference (LSD) test at $p \leq 0.05$. Superscript letters indicate comparisons among treatments within the same storage period.

Fig. 6. *Comparison of surface wrinkling in Alphonso and Bangalora mango fruits at initial stage and at 50% wrinkling stage*

es, thereby enhancing the shelf-life of mangoes.

Firmness (N)

The data presented in Table 3 indicate that the application of AgNP-incorporated biopolymer coatings significantly influenced the firmness of Alphonso and Bangalora mango varieties during the 16 days of storage. Among the treatments, beeswax + AgNPs maintained the highest firmness values for both mango varieties, with 13.02 N in Alphonso and 14.43 N in Bangalora on the 16th day. Beeswax coatings act as a moisture barrier, reducing transpiration and respiration rates, and thereby slowing softening (Marappan *et al.,* 2024). The superior performance of Beeswax + AgNPs aligns with the findings of Basumatary *et al.* (2022) as they reported that wax-based nanocomposites effectively maintained fruit firmness by minimizing enzymatic degradation of cell walls. Conversely, some control fruits were carried forward even after 16 days (though it is not presented in table) exhibited the lowest firmness values after 16 days, with 10.04 N in Alphonso and 12.43 N in Bangalora, indicating faster ripening and softening due to the lack of protective barriers against moisture loss and enzymatic degradation. The present study confirms the previous work of Eshetu *et al. (2019),* who reported that uncoated fruits experienced rapid firmness loss due to increased ethylene production and accelerated metabolic activity.

Total soluble solids (TSS) (^{o}Brix)

Postharvest ripening of mangoes is a major challenge, leading to quality deterioration and reduced shelf life. This study's results evaluate the impact of AgNP-incorporated biopolymer coatings on the TSS of Alphonso and Bangalora mango varieties over a 16-day period, as presented in Table 4. The TSS observed during the early and mid-storage periods, revealed a slowdown of ripening-related metabolic activity. The results revealed that uncoated mangoes exhibited the highest TSS values at all stages, indicating faster ripening. In the initial stages, among the coated samples, Beeswax + AgNPs demonstrated the most significant delay in TSS increase, followed by Chitosan + AgNPs and Arabic Gum + AgNPs. However, in the final stage of analysis, on the 16th day of storage, the TSS values in Beeswax + AgNPs–treated fruits became comparable to those of the control treatment, revealing the natural progression of ripening over extended storage. The ability of biopolymer coatings to slow ripening can be attributed to their regulatory role as semi-permeable barriers, which reduce respiration and ethylene production. The study of Hmmam *et al.* (2021) also demonstrated the effectiveness of AgNP-based coatings in preserving fruit texture and delaying senescence. The low TSS in coated fruits is due to the coating's barrier effect, which reduces respiration and inhibits metabolic activity (Du *et al.,* 2022). The results prove beyond doubt that ripening is delayed in the case of a biopolymer coating, which in fact leads to a longer shelf life.

Total sugars (%)

The application of AgNP-incorporated biopolymer coatings significantly influenced the total sugar content in mangoes during storage, as shown in Table 5. The biopolymer coverings inhibited the accumulation of sugars, indicating a delay in ripening. Among treatments, Beeswax + AgNPs and Arabic Gum + AgNPs resulted in the lowest sugar accumulation at later stages, high-

Table 3. Effect of different biopolymer coatings with AgNPs on the firmness of mango varieties

Treatments		Days of storage			
Varieties	**Bio-polymer with AgNPS**	**4 days**	**8 days**	**12 days**	**16 days**
Alphonso	Control (untreated)	26.376^{e}	16.233^{f}	13.697^{e}	10.047^{h}
Alphonso	Arabic gum + AgNPs	26.570^{e}	18.413^{d}	16.807^{c}	12.497^{cd}
Alphonso	Guar gum + AgNPs	25.987^{e}	17.033^{f}	15.087^{d}	11.313^{fg}
Alphonso	Chitosan+ AgNPs	28.937^{d}	17.147^{ef}	15.337^{d}	11.083^{g}
Alphonso	Beeswax+ AgNPs	28.710^{d}	18.093^{de}	17.127^{c}	13.023^{bc}
Bangalora	Control (untreated)	30.667^{c}	20.027^{c}	16.900^{c}	12.433^{de}
Bangalora	Arabic gum + AgNPs	33.800^{a}	20.847^{bc}	18.327^{b}	13.230^{b}
Bangalora	Guar gum + AgNPs	31.383^{bc}	21.403^{b}	18.030 ^{b}	12.267^{de}
Bangalora	Chitosan+ AgNPs	32.510^{ab}	20.507^{c}	16.810^{c}	11.797^{ef}
Bangalora	Beeswax+ AgNPs	32.880^{ab}	22.440^{a}	20.500^{a}	14.433^{a}
CD 5%		1.684	0.954	0.458	0.689
SE(d)		0.807	0.457	0.219	0.33

Values followed by different superscript letters within the same column differ significantly according to the Least Significant Difference (LSD) test at $p \leq 0.05$. Superscript letters indicate comparisons among treatments within the same storage period.

Table 4. Effect of different biopolymer coatings with AgNPs on the TSS of mango varieties

Treatments		**Days of storage**			
Varieties	**Bio-polymer with AgNPS**	**4 days**	**8 days**	**12 days**	**16 days**
Alphonso	Control (untreated)	10.290^{c}	14.826^{cd}	17.760^{de}	21.387^{bc}
Alphonso	Arabic gum + AgNPs	9.120^{d}	14.077^{de}	16.217^{f}	18.857^{d}
Alphonso	Guar gum + AgNPs	9.043^{d}	13.657^{ef}	16.313^{f}	18.600^{d}
Alphonso	Chitosan+ AgNPs	9.260^{d}	13.963^{e}	17.430^{e}	18.280^{bc}
Alphonso	Beeswax+ AgNPs	8.270^{e}	13.290^{ef}	15.460^{g}	21.4533^{d}
Bangalora	Control (untreated)	12.113^{ab}	16.353^{a}	20.003^{a}	21.273^{bc}
Bangalora	Arabic gum + AgNPs	11.757^{b}	15.170^{bc}	18.283^{bc}	20.900^{c}
Bangalora	Guar gum + AgNPs	12.060^{ab}	15.653^{ab}	18.523^{cd}	23.667^{a}
Bangalora	Chitosan+ AgNPs	12.533^{a}	16.007^{a}	19.210^{b}	22.073^{b}
Bangalora	Beeswax+ AgNPs	10.383^{c}	13.170^{f}	14.860^{g}	21.307^{bc}
CD 5%		0.679	0.791	0.755	0.877
SE(d)		0.326	0.379	0.362	0.421

Values followed by different superscript letters within the same column differ significantly according to the Least Significant Difference (LSD) testat $p \le 0.05$. Superscript letters indicate comparisons among treatments within the same storage period

Table 5. Effect of different biopolymer coatings with AgNPs on the total sugars of mango varieties

Treatments		**Days of Storage**			
Varieties	Bio-polymer with AgNPS	4 days	8 days	12 days	16 days
Alphonso	Control (untreated)	12.560^{a}	13.500^{abc}	16.427^{b}	22.113^{a}
Alphonso	Arabic gum + AgNPs	11.577^{b}	12.533^{d}	15.300^{de}	18.023^{d}
Alphonso	Guar gum + AgNPs	12.360^{a}	12.707^{cd}	15.793^{cd}	18.970^{c}
Alphonso	Chitosan+ AgNPs	12.557^{a}	12.833^{cd}	16.700^{b}	21.253^{b}
Alphonso	Beeswax+ AgNPs	10.893^{bc}	11.067^{e}	14.527^{f}	17.700^{de}
Bangalora	Control (untreated)	12.850^{a}	13.800^{ab}	17.423^{a}	21.350^{ab}
Bangalora	Arabic gum + AgNPs	10.927^{bc}	13.200^{bcd}	15.173^{e}	18.133^{d}
Bangalora	Guar gum + AgNPs	10.597^{c}	12.633^{d}	15.793^{cd}	17.070^{e}
Bangalora	Chitosan+ AgNPs	11.577^{b}	14.233^{a}	16.327^{bc}	20.917^{b}
Bangalora	Beeswax+ AgNPs	10.816^{c}	13.300^{bcd}	15.420^{de}	17.533^{de}
CD 5%		0.756	0.864	0.56	0.825
SE(d)		0.362	0.414	0.269	0.395

Values followed by different superscript letters within the same column differ significantly according to the Least Significant Difference (LSD) testat $p \le 0.05$. Superscript letters indicate comparisons among treatments within the same storage period

lighting their effectiveness in extending shelf life. In contrast, control mangoes exhibited the highest total sugar levels throughout the storage period, confirming rapid ripening due to the absence of a protective barrier or coating. AgNPs reduce metabolic activity and respiration rates, which are key factors in delaying the conversion of starch to sugar (Hmmam *et al.,* 2021). Additionally, Guar gum and Arabic gum coatings have been reported to enhance fruit firmness while maintaining controlled sugar release during ripening (Saleem *et al.,* 2020). These have been reported by Rosman *et al.* (2024), indicating that zinc-oxide nanocomposite-based coatings provide an eco-friendly and effective solution for postharvest management of mango.

Total carotenoids

The study reveals that AgNP-incorporated biopolymer coatings significantly influence the accumulation of carotenoids in mango varieties (Table 6). The control samples exhibited the highest carotenoid content, indicating natural ripening. In contrast, coated samples showed a delayed increase in carotenoids, with beeswax + AgNPs being the most effective in slowing ripening, followed by chitosan + AgNPs, suggesting that wax coatings restrict gas exchange, delaying ethylene production and, consequently, ripening. Alphonso mangoes generally had higher carotenoid content than Bangalora, indicating varietal differences at the genetic entity level which is already an established fact. Over

Table 6. Effect of different biopolymer coatings with AgNPs on the total carotenoids of mango varieties

Treatments		**Days of storage**			
Varieties	Bio-polymer with AgNPS	4 days	8 days	12 days	16 days
Alphonso	Control (untreated)	19.800	24.950^{a}	25.713^{a}	29.016^{a}
Alphonso	Arabic gum + AgNPs	16.777	21.344^{d}	22.633^{ef}	25.837^{e}
Alphonso	Guar gum + AgNPs	17.80	22.147^{c}	23.076^{e}	26.630^{d}
Alphonso	Chitosan+ AgNPs	18.233	22.840^{b}	24.166^{c}	28.180^{b}
Alphonso	Beeswax+ AgNPs	16.713	20.390^{e}	21.783^{g}	24.870^{f}
Bangalora	Control (untreated)	18.823	21.180^{d}	24.850^{b}	28.923^{a}
Bangalora	Arabic gum + AgNPs	16.230	19.893^{f}	22.176fg	26.633^{d}
Bangalora	Guar gum + AgNPs	16.456	19.750^{f}	22.837^{e}	27.146^{c}
Bangalora	Chitosan+ AgNPs	17.350	20.393^{e}	23.683^{d}	27.883^{b}
Bangalora	Beeswax+ AgNPs	16.083	18.640^{g}	21.950^{g}	26.153^{de}
CD 5%		N.S	0.396	0.459	0.504
SE(d)		N.S	0.19	0.156	0.241

NS- Non-significant;Values followed by different superscript letters within the same column differ significantly according to the Least Significant Difference (LSD) test at $p \leq 0.05$. Superscript letters indicate comparisons among treatments within the same storage period.

time, carotenoid accumulation increased in all treatments, but coatings, particularly beeswax and guar gum, effectively slowed this process. The statistical analysis confirmed significant differences between treatments, reinforcing the role of biopolymer-based AgNP coatings in extending fruit shelf life by regulating the carotenoid synthesis. Similar results have been obtained in mangoes coated with alginate-based zinc oxide (Alg-ZnO NPs), revealing that the extension of shelf-life and delayed internal colour change in coated fruit may be due to a slower respiration rate, which indirectly slows chlorophyll degradation and carotenoid production (Hmmam *et al.,* 2023).

The current study provides evidence for the use of biopolymer-based AgNP loadings at a low concentration (10 ppm) to prolong mango shelf life. Additional studies are necessary that would assess food safety and environmental concerns more directly. One of the critical concerns regarding metal particles is safety. The concentrations used in the study are very low, at parts per million. Silver is considered as one among the best for such studies and has been reported in mango (Hmmam *et al.,* 2021). However, to date, there is no reference on the potential use of *Sauropus* for the green synthesis of silver nanoparticles in mango, and this study is the first report of its kind. Also, the safety limits of its use have not been a considered topic for investigation. This is an imperative need in all studies involving the use of metal nanopartilces in food and also demands immediate attention. One aspect of future research could be to examine the premise that non-polar biopolymers, such as beeswax, are more effective at preventing AgNPs from moving into the fruit than polar biopolymers, such as arabic gum or guar gum, due to differences in matrix structure and permeability. Coatings based on chitosan, due to their cationic charge, may also affect AgNP binding strength and release differently during storage. Extensive quantitative migration studies employing elemental or isotopic tracer methods are to be undertaken to determine the extent of AgNPs that have penetrated into the flesh and that can be safely eaten at the concentrations at which it was applied. The assessments based on the above hypotheses will be necessary for determining safe consumable limits, improving combinations of biopolymer and nanoparticle, and ultimately securing regulatory approval for AgNP-based edible coatings for commercial use.

Conclusion

The study highlights the effectiveness and potential feasibility of a novel edible biopolymer coating combined with green-synthesised AgNPs in extending the shelf life and maintaining the postharvest quality of mangoes. Among all the edible coatings used in the study, beeswax and Arabic gum with AgNPs were found to be the most efficient in terms of quality parameters, including retention of fruit firmness, minimisation of physiological weight loss, total sugar content, and carotenoids. The results suggest that nanotechnology-based edible coatings offer a green sustainable approach to enhancing shelf-life and postharvest fruit preservation. More research focused on the assurance of the safety of nanoparticle-based coatings for human consumption will be paramount. This aspect needs to be worked out in detail as the critical limit for human consumption has not yet been defined in case of silver, though it is mostly predominantly used metal nanoparticle in post-harvest studies. Risk assessment, biosafety and regulations for use of inorganic nanoparticles must simultaneously progress with careful scrutiny so that the results obtained which are of immense relevance reach full practical applications. While AgNPs offer antimicrobial benefits, potential risks related to nanoparticle accumulation in human tissues and environmental impact need must be thoroughly investigated and evaluated. The imperative need of the hour is to have in place regulatory frameworks to establish safe critical limits and ensure compliance with global food safety standards.

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Conflict of interest

The authors declare that they have no conflict of interest.

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