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Original Article

Development of Novel Hexanal Nano-Fibre Matrix by Electrospinning for Shelf-life Extension of Mango Fruits

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Abstract *- The current work used electrospinning to create a unique hexanal nano-fibre matrix for the noncontact packaging of mango fruits to improve their shelf life during storage and transportation. Thus, the problem of colour spots is overcome, and the vaporisation of hexanal molecules on the surface of fruits is reduced during postharvest treatment. Hexanal release from the nano-fibre matrix was confirmed using gas chromatography-mass spectrometry. The scanning electron microscope exposed nanowires with diameters ranging from 195.5 to 345.8 nm. The FT-IR spectra revealed the distinctive peak of hexanal in the wavenumber region of 1894-1147cm-1. Applying the hexanal nano-fibre matrix to green matured mango fruits in ambient environments resulted in a 14-day shelf-life extension. In comparison, the control samples remained fresh for only 6 days. The effect of the hexanal nano-fibre on mango sensory qualities revealed that freshly picked mangoes scored higher values in appearance, color, texture, flavour, and overall acceptability than treated fruits. The treated fruits had better quality qualities than the control fruits, such as decreased physiological weight loss, increased firmness, lower percentage decay, higher pH, and better color.*

Keywords *- Electrospinning, Food security, Hexanal, Postharvest loss, Shelf life.*

1. Introduction

Mangoes are among the most popular fruits worldwide and are a substantial tropical fruit production. It belongs to the Anacardiaceae family and is distinguished by its minimal calorie content [1]. It is a good source of essential nutrients, such as dietary fibre, vitamins, minerals, and polyphenolic flavonoid antioxidants, and it is free of cholesterol. Mango potentially can improve the immune system and modulate blood pressure, in addition to possessing anti-cancer properties [2]. Mango fruit consumption has been shown to have prospective health benefits by reducing the incidence of specific malignancies and cardiovascular diseases [3]. The fruit's rapid maturation postharvest severely limits its long-distance commercial transport and storage due to its extreme perishability and climacteric state. The maturation and senescence of the fruit are accelerated by the respiration rate, which leads to a significant postharvest loss in quality and an increase in water loss [4]. The primary cause of substantial postharvest losses is the perishable nature of the Fruit, which is further exacerbated by the lack of appropriate postharvest technology to extend the shelf life [5]. Various postharvest technologies have been developed and implemented to extend the shelf life of mangoes and reduce postharvest losses. The following technologies are included in this list: an active modified atmosphere [6], a dynamically controlled atmosphere [7], ethylene inhibition technology, thermal treatments, consumable coatings, preservation by chemical and natural substances [8], and hexanal technology [9]. Hexanal technology offers a more hygienic and secure preservation method. The technology is economically viable and ecologically sustainable [10].

Hexanal molecules are naturally occurring volatile produced when plant tissues are injured [10]. It inhibits phospholipase-D, limiting membrane disintegration, which strengthens the fruit skin and extends the shelf life of fruits [11]. Hexanal has the chemical formula $C_6H_{12}O$ and a molecular mass of 100 g/mole. It is a fluid at ambient temperature (25 ºC), with a melting point of -20 ºC and a boiling point of 120 ºC [12]. At 20 ºC, it has a minimum vapor pressure of 10 mmHg and easily evaporates at higher temperatures [9]. Hexanal is found in about 300 normal sources, like apples, apricots, bananas, sour and sweet cherries, citrus peel oils and juice, berries, and guavas [9]. Hexanal treatments, both pre-harvest and postharvest, have shown encouraging results in extending the shelf life of a

variety of fruits, including bananas [5], sweet cherries [13], peaches, strawberries, and veggies such as broccoli, tomatoes, and diverse fresh cut veggies. The application is possible for flowers, such as carnations and roses [14, 15].

According to reports, applying hexanal formulations directly to agricultural produce leaves persistent traces, such as color spots or patches, prompting the development of other treatment methods. Electrospinning, in particular, has emerged as a viable approach to encapsulating volatile compounds in nanotechnology. Encapsulating bioactive agents like hexanal within nanofibers enhances packaging systems' mechanical and barrier qualities, thereby ensuring the active components are protected from external influences and allowing for regulated release [42].

The release behaviour of volatile compounds is modulated by encapsulating them in electrospun fibres, which reduces their volatility and improves their efficacy [33]. This research fabricates a hexanal nano-fibre matrix on an aluminium substrate using electrospinning, characterises the nano-fibre morphology and release profiles, and employs it in the storage study of mango fruits utilising a noncontact delivery strategy to prolong shelf life without residue on the mangoes. This study will first reveal the contactless approach of hexanal nano-fibre matrix distribution on mangoes to extend shelf life. The current research aims to enhance the works regarding the innovative delivery of hexanal formulation to prolong the shelf-life of fruits like mangoes.

2. Materials and Methods

2.1. Fabrication of Nanofiber Matrix

PVA solutions were generated at concentrations of 5%, 7%, 10%, 13%, and 15% (w/w) by thawing PVA in 10 mL of purified water at 60°C while stirring for 4 hours at 300 rpm. To make a 50% β-cyclodextrin solution, 5 g of β-cyclodextrin was gradually added to 10 mL of purified water at 60 °C. A borosilicate hot plate magnetic stirrer at 300 rpm was used for 4 hours to obtain a milky solution. Electrospinning solutions were prepared in a 1:2:5 ratio, using 1 g of hexanal, 2 g of PVA solution at various concentrations (5%, 7%, 10%, 13%, and 15%), and 5 g of (50%) β-cyclodextrin solution concentration based on mass. The mix was agitated for 3 hours at room temperature to ensure homogeneity before electrospinning.

The spinning solutions were electrospun into nanofibers using the monoaxial conveyance technique. The mixed solutions were loaded into a 2.5 mL flexible needle fitted with a needle receptacle on the electrospinning device (ESPIN NANO Model, Astronomy Apparatus and Company, Chennai). The needle was positioned horizontally using a needle pump, and the electrode of the high-voltage power source was connected to the metal needle tip. The applied voltages varied from 25 kV to 30 kV. The solution flow rate was varied between 0.1 and 0.5 mL/h.

Table 1. Various process parameters for electrospinning of the HNFM

S/No	Conc. (%)	Voltage (kv)	Flowrate (mL/h)	TCD (cm)	Diameter of fibre (nm)
1	5	25	0.1	10	80
2	7	26	0.2	15	190
3	10	27	0.3	20	200
4	13	28	0.4	25	420
5	15	30	0.5	30	580

Fig. 1 Image of the electrospun HNFM

The working distance between the needle tip and the ground electrode varied from 10 to 30 cm. Nanofibers were deposited on a 30 × 30 cm² metal template. Table 1 shows the parameters for electrospinning nanofibers. The electrospun hexanal nano-fibre matrix (HNFM) under optimal conditions (1 g hexanal, 2 g of 7% PVA solution, 5 g of 50% β-cyclodextrin solution with 0.2 mL/h flow rate, 26 kV voltage, and 15 cm tip to collector distance (TCD)) was identified as the superior fibre matrix and characterized appropriately. Figure 1 depicts the picture of the fabricated HNFM.

2.2. Characterizations of the Fabricated Nanofiber Matrix

The fabricated matrix was examined with a scanning electron microscope (Quantas 250, FEI, Netherland), a transmission electron microscope (FEI Technai Spirit, Netherlands), and Fourier transforms infrared spectrometry (Nicolet Is10, Thermo-Scientific). This study was carried out at the Center for Agricultural Nanotechnology, Tamil Nādu Agricultural University (TNAU), Coimbatore, India.

2.3. Released Pattern of Hexanal from the HNFM Using GC-MC

The Thermo Scientific Trace GC Ultra Multi-Channel chromatograph was employed in conjunction with a Thermo Scientific DSQ II quadrupole mass spectrometer to analyse the release profile of hexanal from the matrix. Hexanal was isolated using helium as the carrier gas in a 5% phenylmethyl silicone fused silica capillary column. The column temperature protocols were established at 207 °C, with initial increases to 50 °C and 150 °C and subsequent incremental increases to 250 °C. Ions with mass values of 44 and 56 were employed to quantify hexanal. The Triplus RSH Headspace

autosampler facilitated the extraction and introduction of samples with a 2.5 mL and 65 mm syringe. A 1 cm x 5 cm segment was excised from the HNFM and placed in 20 mL containers for the analysis of hexanal release. Vapour samples were collected at 30-minute intervals for 7 hours, as described by Jash et al. [41]. Subsequently, an autosampler was employed in the GC-MS laboratory to analyse the samples.

2.4. Application of the HNFM and Assessment of Fruit Quality Parameters

2.4.1. Application of the HNFM and Assessment of Mango Fruits

The mangoes were obtained from a cultivator in Coimbatore, TNAU, India, located at (10º 18 20 latitude and 77° 62 12 long). Uniformly sized fruits that were intact were selected and transported to the Centre for Agricultural Nanotechnology at TNAU in Coimbatore, India. The fruits were sanitised with a 2% sodium hypochlorite solution for five minutes and, subsequently, air dried in the shade before the treatments. The fruits were divided into two groups: Lot 1, which consisted of control (untreated) fruits, and Lot 2, which was treated with the hexanal nano-fibre matrix. Lot 1 was put in a plastic crate measuring 20 × 40 × 60 cm^3 and was used to hold the control fruits. The hexanal nano-fibre matrix was sectioned into 5 × 5 cm^2 sections and placed on top of the inner fruit packet boxes (15 × 25 × 35cm^3) before sealing.

For Lot 2, the hexanal nanofiber matrix was cut into pieces of size 5 × 5 cm^2 and placed directly on top of the fruit packaging box (35 × 25 × 15 cm^3) and then closed. As the fruits respire, the humidity of the packaging box increases, prompting the release of hexanal from the HNFM, which is then absorbed by the fruits (contactless treatment). The digital data recorders were used to record the room temperature and relative humidity, which resulted in values of 30±2˚C and 62±2%, respectively. The shelf life was quantified as the number of days it took for the fruits to reach an optimum eatable stage from the time of experimentation. To ascertain precise results, the experiment was conducted three times.

- Fruit Firmness

Mangoes from each group (Lot 1: untreated and Lot 2: preserved) were evaluated for hardness with a penetrometer, piercing to a deepness of 1 cm. The measurements taken in (kg) were converted and represented in N/mm.

- Fruit Color

Fruit colors were assessed using a portable color mass spectrometer (Hunter Lab, Mini-ScanEZ, 4500L). The fruits were placed at the instrument's port, with the side facing the port. Precautions were taken to ensure that the fruit flushed with the port and was completely obscured by the fruit. The results were examined as follows: The L* measure compares light and dark, with lesser values (0 - 50) indicating darkness and high values (51 - 100) indicating brightness. The a* represents red vs green measurements, with positive values indicating red and negative values indicating green. The b* measures yellow and blue measurements, with positive values denoting yellow and negative values indicating blue.

- Physiological Weight-Loss

Physiological weight loss was determined by subtracting the final weight from the initial weight of the mangoes and recording as per cent weight loss regarding the original weight (Equation 1).

$$Pwl = \frac{w_i - w_f}{w_i} \quad (1)$$

where;
Pwl is physiological weight-loss (%)
w_i is initial-weight (g)
w_f is final-weight (g)

- Percentage Fruit Decay

Mangoes with more than 15% superficial decay owing to softening or bacterial assault were deemed unsatisfactory, and the decay percentage was determined using this metric [16]. The Percentage Decay (PD) was calculated by eliminating the spoilt and decayed fruits and dividing by the total percentage, as shown in Equation 2.

$$\mathrm{PD}(\%) = \frac{\mathrm{Nd}}{\mathrm{Tn}} \quad (2)$$

where;
PD fruit decay (%)
Nd is the amount of decayed mangoes
Tn is the amount of mangoes

- pH and Titratable Acidity (TA)

The Digital pH meter 11 model, HI Hanna Apparatuses, Italia) was used for the measurement of the mango juice pH whereas titratable acidity (citric acid %) was measured by titrating 5 mL of mango juice with 0.1N Na hydrated oxide utilizing phenolphthalein as a gauge [17]. Acidity was calculated and expressed as citric acid percentage.

- Total Soluble Solids (TSS)

TSS values were measured in degrees °brix and were directly measured using an Abbe refractometer (Bellingham and Stanley Ltd Model, England) by applying a droplet of the supernatant onto the optical prism of the equipment. The TSS data were recorded using the ocular and represented as °Brix [18]. The procedure was conducted three times, and the average values was documented as the refractive index.

- Sensory evaluation

Sensory evaluation was conducted by descriptive analysis. A panel of semi-trained judges evaluated the mango fruit for appearance, colour, flavour, taste, and overall acceptability using a 9-point hedonic scale of twenty trained laboratory technologists. This was performed in a specialised sensory testing environment featuring partitioned booths. The degrees of preference, as indicated by the descriptive phrases,

were subsequently transformed into scores: 9 for like extremely, 8 for like very much, 7 for like moderately, 6 for like badly, 5 for neither like nor dislike, 4 for dislike poorly, 3 for dislike moderately, 2 for dislike very much, and 1 for dislike exceedingly [19].

2.5. Statistical Analysis

The data collected in the work were examined utilising the statistical software SPSS. ANOVA was used to identify significant differences among the means. Significance was established at $p<0.05$.

3. Results and Discussion

3.1. Electrospinning

3.1.1. Effect of Solution Concentration

The findings show that appropriate fibre creation is prevented at extremely high concentrations due to excessive viscosities, whereas beads are generated at very low polymer solution concentrations. PVA concentrations greater than 10% generated a ribbon. Bead production was seen at low PVA solution concentrations (<5%). As a result, a 7% PVA concentration was found to be ideal for producing an excellent nano-fibre operating state free of ribbon or bead formation. As the concentration of the PVA solution rose, the nanofibers' diameter grew gradually and considerably. Excessive PVA concentrations produced ribbon and bead morphologies owing to lower viscosity and surface tension. The findings are consistent with those of [20], who observed that increasing the concentration of the polymer solution causes an increase in fibre diameter. The study supports the findings of [21], which showed that solution thickness and concentration had comparable impacts on fibre shape.

3.1.2. Impact of Applied Voltage

The electrical energy used during electrospinning is critical in defining the nanofiber size. When the critical current is reached, fluid jets erupt from the syringe tip as the applied voltage exceeds the solution's surface tension forces, producing nanofiber. The voltage was found to be exactly proportional to the fibre diameter. The optimal voltage for an excellent nanofibre was 26 kv. This is consistent with the findings of [22], which suggested that the applied voltage is an important component in determining the diameter of nanofibers during electrospinning. [23] found similar findings, suggesting that increasing the applied voltage from 25 to 45 kV leads to a larger average nanofiber diameter.

3.1.3. Impact of Solution Flowrate

The flow rate was chosen to allow enough time for the solvent to evaporate. It was discovered that increasing flow velocity resulted in thicker, beaded fibres. This may be due to increased fluid outflow from the spinneret climax. The solution flow rate is directly related to fibre diameter. The flow rate of the polymer solution influences the thickness of nanofibers. A 7% PVA solution was electrospun at a continuous voltage and flow rate of 0.1-0.5 mL per hour. The flow velocity and viscosity of the polymer solution are critical factors for creating appropriate fibres during electrospinning. The thickness of the nanofiber was affected by the polymer solution's flow rate. The results show that increasing the flow rate increased the thickness of the nanofiber, which is most likely due to increased fluid ejection from the spinneret tip. [24] discovered that the fibre diameter corresponds with the solution's feed rate; therefore, choosing a flow rate that enables enough time for solvent evaporation is critical. The ideal flow rate for improved nanofiber formation was determined to be 0.2 mL/h, consistent with findings from [25], which revealed a relationship between nanofiber diameter and solution flow rate.

3.1.4. Impact of Tip-to-Collector Distance

To investigate the impact on fibre thickness, a 7% PVA solution was electrospun at varying TCDs (10-30 cm). A particular distance was determined to be essential for the optimal synthesis of fibres. The findings suggest that beads were produced at distances that were both exceedingly low and unduly high. This may be attributed to the solvent dispersion not being sufficient at smaller TCDs, resulting in beaded fibres.

Conversely, the solvent had an inordinate amount of distance to disperse at a substantially greater distance. The optimal TCD for achieving maximal fibre development was 15 cm. Additionally, [26] found that beaded fibres were generated at both exceedingly low and excessively high distances during the electrospinning of nanofibers. However, the impact of TCD on fibre morphology is less pronounced than that of other variables, as demonstrated by [25].

3.2. Surface Morphology

Figure 2a depicts an SEM image of the electrospun HNFM. Nanowires could be sensed on the superficial. The nanowire diameter varied from 195.5 to 345.8 nm. Figure 2b depicts a transmission electron microscopy depiction of the fabricated HNFM. A bulge with a diameter of 648 may be noticed on a nanowire. The swelling might be attributed to the PVA's inflammation properties [27,28]. The nanofibre comprises two concentric rings, the inner one representing the hexanal molecules. The hexanal component of the nanofibre measured 401 nm out of a total diameter of 648 nm. This finding is consistent with other literature publications [29, 30].

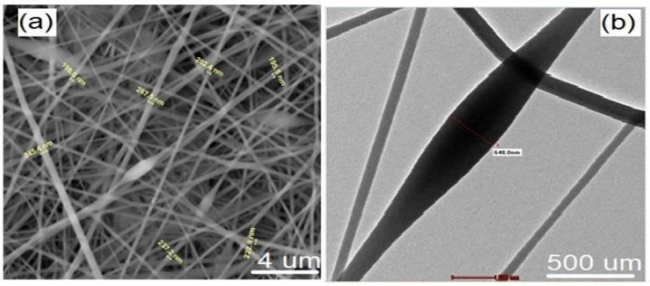

Fig. 2(a) SEM image of the electrospun HNFM, (b) TEM micrograph

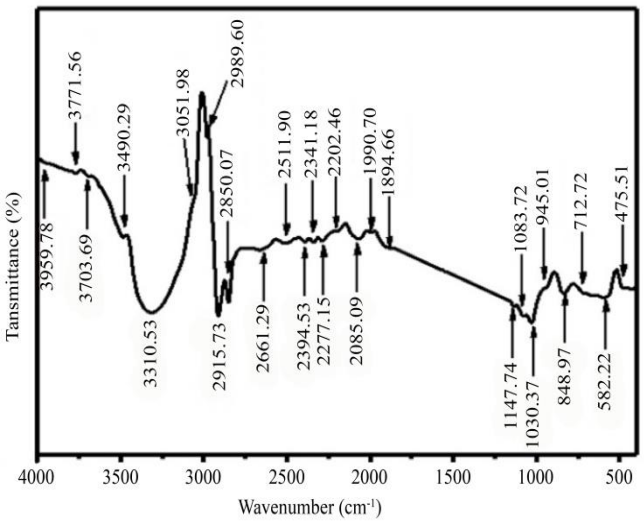

Fig. 3 FT-IR spectrum of the electrospun HNFM

3.3. Fourier Transform-Infrared Spectrometry

The FT-IR spectrum of the electrospun HNFM is depicted in Figure 3. The mode at 2915 cm-1 might be traced to the aldehydes' functional assemblage, which regularly appears as a shoulder joint top to the precise side of the alkyl C–H stretch. The carbonylic stretch C=O of flooded aldehydes appeared from 1894 cm-1. Another aldehyde group of O=C–H stretching could be seen in the region 2915-2850 cm-1.

The β-cyclodextrin band was observed at 2915 and 1030 cm-1, whereas that for polyvinyl alcohol was centred at 1147 cm-1, and that of hexanal seen at 2989 cm-1, consequently corroborating the several components existing in the fabricated hexanal nano-fibre matrix. Comparable results in FTIR were reported by [31], which long-established the existence of the essential components in the fibre mat. The β-cyclodextrin absorptions observed at 3771, 2915, 1147, and 1030 cm-1 could be associated with the symmetric and antisymmetric stretching of OH, CH_2, C-C and O-H bending vibrations, respectively. The present result agrees with the literature reports [32].

3.4. Released Pattern of Hexanal Using GC-MC Studies

The study examined the release of hexanal from a nano-fibre matrix at 90% relative humidity (RH), using a PVA, β-cyclodextrin hexanal inclusion complex (1:2:5) over 7 hours (Figure 4). The nano-fibre matrix demonstrated the ability to store and release hexanal vapour slowly and steadily for 7 hours at 90% RH. The release was triggered by PVA's hydrophilic nature, which caused the fibre to swell and dissolve at 90% RH.

Water particles reduced the interface among the hexanal, PVA, and β-cyclodextrin merger, increasing the hexanal's diffusivity over the fibre mat to the outside atmosphere. This finding is comparable what was previously reported by [11] and [33]. The hexanal vapour release pattern was established with a diffusion kinetics classical of Hixson Crowell with a reversion coefficient value (R2 = 0.80) comparable to the outcomes stated by [41]. The data showed that the loaded nano-fibre contributes to the slowing down and controlled release of hexanal, which is time-dependent.

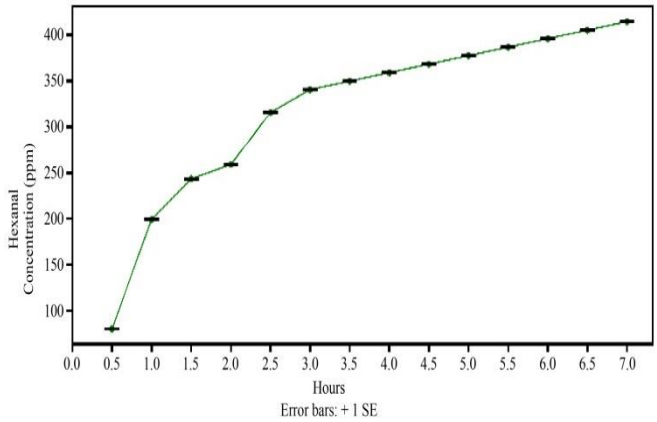

Fig. 4 Hexanal released pattern of the HNFM using the GC-MC

3.5. Effect of the HNFM on the Shelf life of Mangoes

The impacts of the HNFM on the visual quality of mango fruits throughout the 14-day storage period are illustrated in Figures 5-8. The initial appearance of the treated mangoes and the untreated samples was comparable (Figures 5a and 5b).

By day 3, significant alterations in the physical appearance of the control samples were evident, characterized by yellowing and shrinkage, indicative of water loss from the mango fruits (Figure 6a).

Nonetheless, the treated samples retain their freshness and verdancy (Figure 6b). After six days of storage (Figure 7a), deterioration occurred in the control samples, but the treated samples only exhibited initial signs of ripening (Figure 7b).

This indicates that the therapy inhibits the ripening of mango fruits. The utilisation of the HNFM prolonged the shelf life of mango fruits by fourteen days (Figure 8b), while the untreated mangoes remained appealing for just six days (Figure 6a).

The findings indicated that mango fruits treated with hexanal nano-fibre matrix had an extended shelf-life compared to the control fruits. The information corroborates the findings of [34] regarding pre-harvest spray and [35] with postharvest dip treatments utilising hexanal preparation.

This data strongly aligned with additional studies [14, 9] regarding extending fruit's shelf life through hexanal formations, including tomatoes, oranges, and mangoes. The outcomes indicated that the preserved fruits had a lengthier shelf life than the untreated group.

Fig. 5 Appearance of the mango fruits (on day 1 (a) Untreated, and (b) Treated fruits

Fig. 7 Appearance of the mango fruits on day 6 (a) Untreated and (b) Treated fruits

Fig. 6 Appearance of the mango fruits on day 3 (a) Untreated and (b)Treated fruits

Fig. 8 Appearance of treated mango fruits on day 9 (a) and day 14 (b) Treated fruits

3.6. Effect of the HNFM Treatments on the Shelf-Life of Mangoes

3.6.1. Effect of HMFM on Physiological Loss in Weight

The effect of the HNFM treatment on weight loss, changes in firmness and percentage decay in treated mango fruits is presented in Table 2.

Table 2. Effect of the HNFM treatments on Pwl, firmness, and per cent decay of mangoes

Sample	Pwl	Firmness	Percent Decay
Control	9.4±0.0[a]	3.2±0.0[a]	9.31±0.0[a]
Treated	3.3±0.0[b]	11.6±0.1[b]	1.0±0.0[b]

Notes: significance difference $p<0.05$, (a, b): columns with dissimilar and similar superscripts show significant level and non-significant, respectively

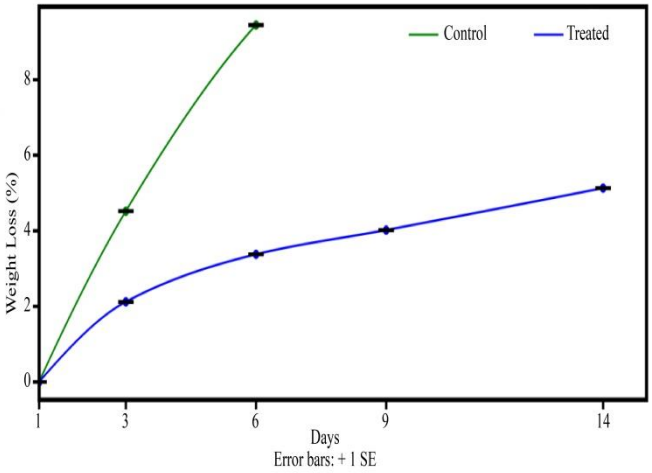

Fig. 9 Effect of the HNFM treatment on Pwl of mangoes. Bars in the line graph signify the standard error of 3 repeats

The Pwl values escalated consistently with the progression of storing times for both the untreated and preserved fruits (Figure 9). The Pwl was greater in the control samples compared to the treated fruits, although this difference was not statistically significant ($p<0.05$). This observation aligns with previous findings on postharvest treatment using hexanal as described by [35]. The reduced percentage of Pwl in treated mango fruits may be ascribed to the inhibition of phospholipase-D enzymes by hexanal, which mitigates water loss, dehydration, and shrinkage in the treated fruits, as previously described by [14, 34]. The Pwl is also ascribed to the capacity of hexanal formulation to enhance skin thickness. This validates the efficacy of the hexanal nanofiber matrix as a method for prolonging the shelf life of fruits.

3.6.2. Effect of the HNFM on Firmness of Mangoes

During the storage period, the firmness of both the untreated and treated fruits decreased, suggesting that they were ripening (Figure 10). However, there were no significant differences in the mean values of firmness. The control fruits' firmness decreased from 15.43 to 3.24 N/mm over the course of six days of storage, whereas the treated fruits' firmness decreased from 15.43 to 11.64 N/mm.

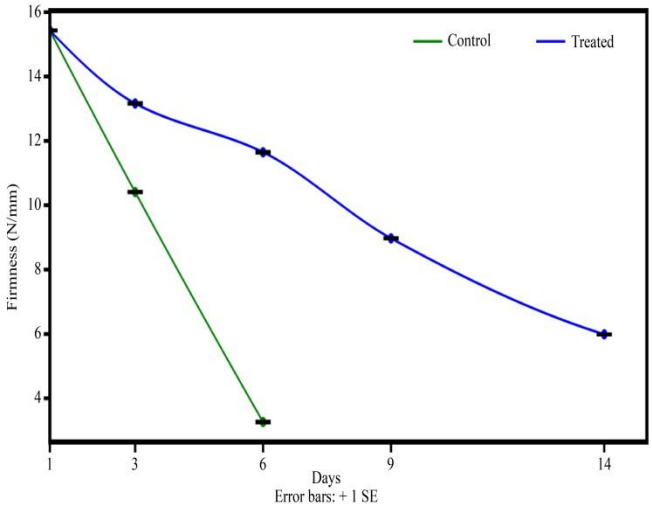

Fig. 10 Effect of the HNFM treatment on firmness of mangoes

The control fruits exhibited a 78.88% reduction in hardness, whereas the treated fruit exhibited a 24.51% reduction in hardness. This may be attributed to fruit softening, which is characterized by the disintegration of cellular walls, primarily as a result of the solubilization and depolymerization of pectin [35]. The hexanal nanofiber matrix impeded the maturation processes during storage. Hexanal is a potent inhibitor of Phospholipase D, which in turn slows down the ethylene-induced maturation and softening of produce [36]. According to numerous reports, the application of hexanal as a preharvest aerosol or postharvest immersion leads to the thickening of cell walls, thereby enhancing the firmness of both tropical and temperate fruits [13, 37]. However, the disadvantage of this method is the emergence of color spots or patches on the fruit's surface, making it unattractive.

3.6.3. Effect of the HNFM Treatment on the Decay of Mangoes

Fruits that were deemed unsuitable were those that had over 15% of their surface deteriorated due to fragility or microbial infestation. This option was employed to ascertain the decay percentage. In comparison to the control group, fruits that were treated with hexanal exhibited a lower degradation percentage. On the sixth day, the control fruits exhibited a degradation rate of 3.51%, whereas the treated mango fruits exhibited a decomposition percentage of only 0.36%. A significant discrepancy in degradation percentages was observed between the control (9.3±0.0a) and treated (1.0±0.0b) fruits (Table 2). This may be attributed to the antibacterial characteristics of hexanal that combat bacterial presence in fruits, as indicated by [34]. This outcome aligns with research on guava fruits subjected to a 0.015% hexanal formulation, which demonstrated minimal deterioration occurrence, diminished PMF action, enhanced hardness, TSS, TA, pectin, and phenolic content while maintaining quality for up to four weeks in mango fruits [38].

3.6.4. Effect of the HNFM Treatment on TSS Contents of Mangoes

Figure 12 illustrates the impact of the HNFM treatment on the TSS value of mango fruits. The TSS content in the mango fruits increased as they ripened for both the control and hexanal-treated fruits. As the fruit progressed in its maturation process, the rate of TSS increase progressively decreased. The TSS content of the control and treated fruits did exhibit a significant difference ($p<0.5$) (Table 3), and the control fruits exhibited the greatest TSS mean values. This could be attributed to the slower maturation of the hexanal-treated fruits. Hexanal has been reported to impede the maturation and softening of fruits induced by ethylene [38]. The conversion of starch into simple sugars, such as glucose, fructose, and sucrose, may cause an increase in TSS during storage, which subsequently results in changes in flavor. This outcome is consistent with the findings of [34].

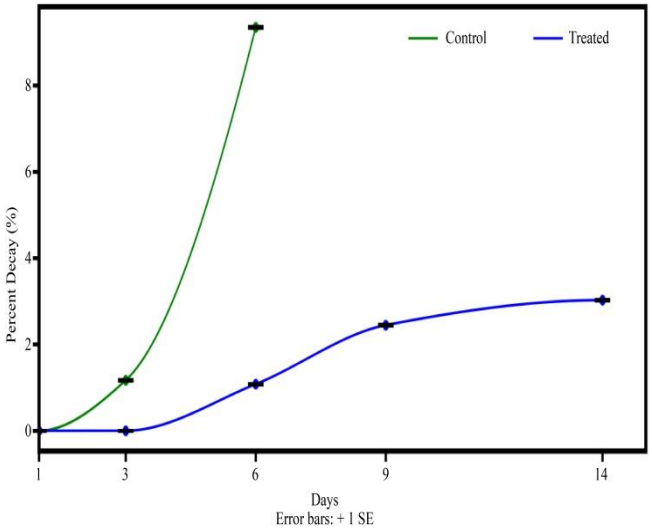

Fig. 11 Effect of HNFM treatment on the decay of mangoes

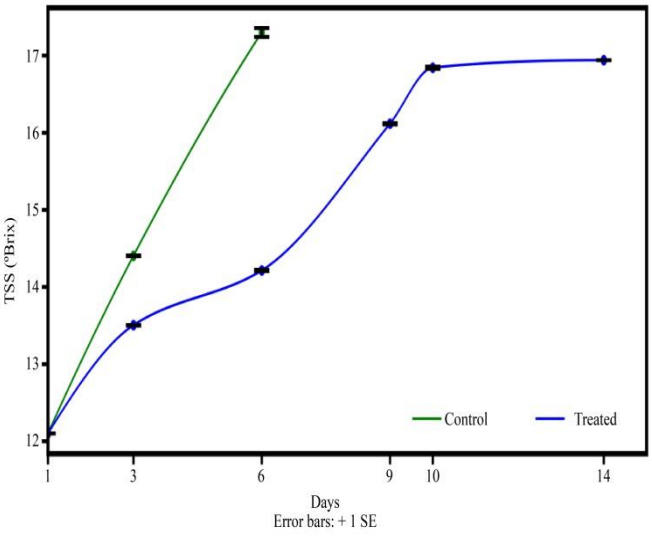

Fig. 12 Effect of the HNFM treatment on the TSS content of mangoes

3.6.5. Effect of the HNFM Treatment on Titratable Acidity of Mangoes

Figure 13 demonstrates the influence of hexanal treatments on the titratable acidity of mango fruits. The mean TA values of mango fruits were observed to decrease gradually as the storing time was extended for both untreated and preserved mangoes. However, the mangoes treated with hexanal experienced a slower rate of TA value reduction. After six days, the data showed that the titratable acidity of control mango fruits decreased by 23.97 per cent, while treated mango fruits had a reduction of 19.89 per cent. The utilization of organic acids during maturation and the initiation of senescence may lead to a decrease in the total acidity of the fruits. The reduced decline in the treated fruits may be attributed to postponed maturation and a reduced respiration rate. [35] has documented comparable findings regarding EFF in tomato crops. In a similar vein, [15] documented an analogous trend of TA value in tomatoes that were subjected to a 0.02% hexanal solution EFF immersion treatment for 2.5 minutes.

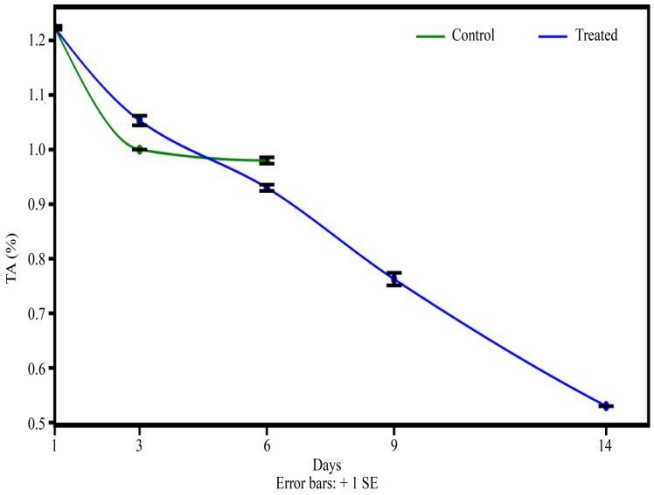

Fig. 13 Effect of the HNFM treatment on the TA value of mangoes

3.6.6. Effect of the HNFM Treatment on Changes in the Color of Mangoes

The impact of hexanal nanofiber matrix treatment on the color alteration of mango fruits is illustrated in Figure 14, while the overall color index of the mango fruits is illustrated in Figure 15. The color values (L*, a*, b*) of the mango fruits were observed to increase during storage for both the untreated and treated mangoes (Figure. 14). The fruit's luminosity, the degradation of chlorophyll during maturation, and the rise in b* values due to an increase in carotenoid concentration as the fruit ripens can all be attributed to the variation in L* and a* color values. The total color index values (L*, a*, b*) of mangoes in storage were significantly influenced by the nanofiber treatment (Table 3). The degree of greenness is represented by the intensity values, which are represented as a*. The value gradually decreased, suggesting that the maturation process is progressing.

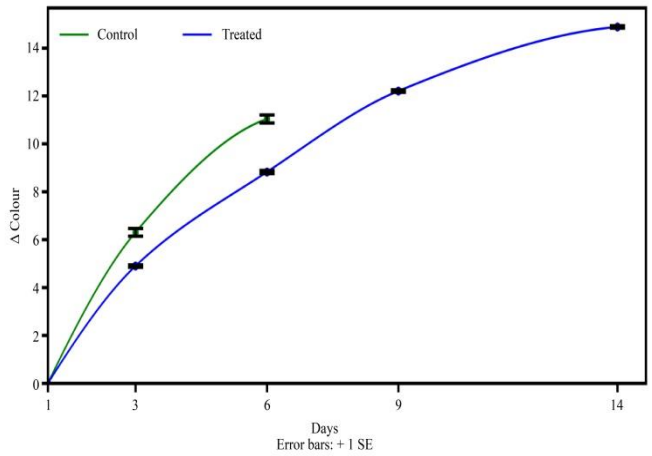

Fig. 14 Effect of the HNFM treatment on color changes in mangoes

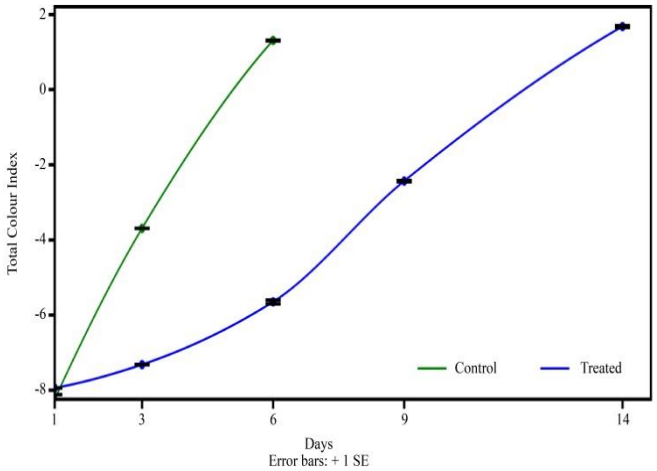

Fig. 15 Effect of the HNFM treatment on the total color index in mangoes

Table 3. Effect of the HNFM treatment on TSS, TA, color change and total color index in mangoes

Samples	TSS	TA	Color change	Total color index
Control	17.3±0.0^{a}	0.98±0.0^{b}	11.0±0.1^{a}	1.3±0.0^{a}
Treated	14.2±0.0^{b}	0.93±0.0^{a}	8.8±0.0^{b}	-5.6±0.0^{b}

Notes: significance difference p<0.05, (a, b): columns with dissimilar and similar superscripts show significant level and non-significant, respectively

The fruits treated with hexanal exhibited reduced (more negative) values, demonstrating its effectiveness in fruit preservation and indicating that the maturation process was slowed. This is consistent with the findings recorded by [13, 38].

3.6.7. Effect of the HNFM treatment on sensory attributes of mangoes

Figure 16 presents the effect of the HNFM treatment on the sensory attributes of mangoes. The sensory characteristics were obtained by comparing freshly harvested and treated mango fruits.

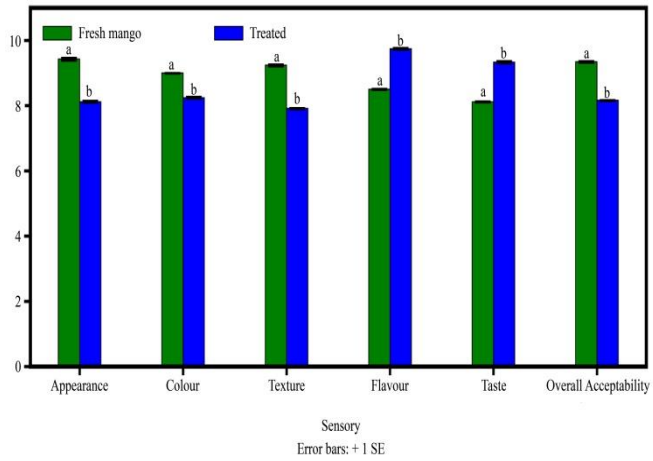

Fig. 16 Effect of the HNFM treatment on sensory attributes of freshly harvested and treated mango fruits

Notes: significance difference p<0.05, (a, b): bars with dissimilar and similar superscripts show significant level and non-significant, respectively.

Economic Feasibility Study

The cost of production of the HNFM for shelf-life extension of mango fruits is presented in Table 4.

Table 4. Cost of production of the HNFM

S/No	Materials	Quantity	Unit Cost (₹)	Total Amount (₹)
1	Hexanal	1 g	23.55	23.55
2	PVA	2 g	0.57	1.14
3	β-cyclodextrin	5 g	8.52	42.6
4	Aluminium Foil	25x25 sq. sheet	1.5	1.5
	Total			**₹68.79**

Notes: 30 pieces of size 5x5 cm2 of the HNFM were developed on the Aluminium foil. Dividing the cost by 30 gives 2.29 rupees per HNFM.

The control fruits were not considered for the sensory attributes because they were already spoiled on the 14th day and rendered unsuitable for observations. The sensory evaluation results regarding the impact of hexanal treatment on mango fruits, assessed using a 9-point hedonic scale, indicated that freshly harvested mango fruits demonstrated superior scores in appearance, colour, texture, and overall acceptability relative to the treated fruits. However, the mango fruits treated with hexanal had significantly higher values in flavour and taste compared to the control, indicating greater palatability. Moreover, the treated fruits exhibited additional attributes that exceeded those of the control fruits, including reduced Pwl, increased firmness, reduced decay percentage, lower TSS and TA, and enhanced colour.

The hexanal nanofibre matrix is extremely excellent in preserving and storing mango fruits. A comparison of the HNFM technology with others, like edible coating technologies for shelf-life studies of mangoes, showed that the HNFM-treated mango had better results in terms of weight

loss, colour changes and shelf-life during storage as compared to the report by [39] of mango-treated with chitosan coating enriched with cinnamon oil where the treated fruits stayed good for only 12 days at 30 °C. Also, in another study conducted by Passafiume et al. [40], mango fruits treated with neem oil edible coating during cold storage stayed good for 9 days only, which was also lesser than that of HNFM-treated mango fruits which had a shelf life of 14 days. This further indicates the superiority of the HNFM as an innovative technology that can be used to transport and store mango fruits.

From the cost of fabrication of the HNFM (Table 4). The total cost of fabricating 30 pieces of 5x5 cm^2 HNFM on an aluminium foil sheet is 68.79 rupees. This means that one of the HNFM of size 5x5 cm^2 will cost 2.29 rupees. Moreover, one of the HNFMs is needed to preserve 3 kg of mango fruits. At present, a Kg of mango fruits at Coimbatore, India, costs 70 rupees. Therefore, 3 Kg of mango will cost 210 rupees. This means that a farmer will need just 2.29 rupees to preserve his 3 Kg of mango, which would cost 210 rupees. This shows that he will save 207.71 rupees using the HNFM to preserve his mango fruits for 14 days. Ordinarily, the mango fruits would have spoiled on the 6th day of storage if they had not persevered with the matrix. This will be an ideal value addition to existing packaging boxes to extend the shelf-life of fruits by investing just 2.29 rupees per HNFM; 3 kg mango fruit shelf-life will be extended for 14 days.

4. Conclusion

This research developed and utilized a novel hexanal nano-fibre matrix for the shelf-life extension of mango fruits. The fabricated nano-fibre matrix was characterized using SEM, TEM, and FT-IR measurements, confirming hexanal molecule loading within the nanofiber matrix. The nano matrix had an amorphous crystalline structure and a nanowire shape. The FT-IR spectra displayed many bands corresponding to the molecular bonds of the different components of the nano matrix. The distinctive peak of hexanal was seen in the range of 1894-1147 cm^{-1}. Shelf-life experiments demonstrated that the developed HNFM prolonged the shelf-life of mango fruits by up to 14 days under an ambient environment, whereas untreated fruits stayed good for 6 days only. The treated mango fruits also exhibit reduced Pwl, increased firmness, reduced percentage decay, lower TSS and TA, and enhanced color, attributes of heartier fruits. The findings indicate that the hexanal nano-fibre matrix is efficient in slowing down ripening and prolonging the shelf life of mangoes. The effectiveness of the novel HNFM in extending the shelf life of mango fruits will have significant economic and environmental benefits, especially in African countries like Nigeria, where uninterrupted/steady public electricity supply for running cold rooms is lacking.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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