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Development and Evaluation of Nanostructured Antimicrobial Systems for Enhancing Shelf Life and Quality Retention of Perishable Food Products

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Abstract

The rapid spoilage of perishable food products poses a major challenge to global food preservation and safety. Conventional preservation methods such as refrigeration and chemical additives often fail to maintain product quality during storage. This study aimed to develop and comparatively evaluate three nanostructured antimicrobial systems an essential oil based nano emulsion, silver nanoparticles (AgNPs), and a chitosan polyvinyl alcohol (PVA) nanofiber coating for their ability to enhance shelf life and quality retention of fresh cut strawberries. Each system was synthesised and characterised for particle size, morphology, and stability before application. The nano emulsion droplets averaged 118 nm in size, AgNPs 44 nm, and nanofibers 170 nm, confirming nanoscale uniformity. Antimicrobial assays showed that AgNPs exhibited the highest inhibition against Escherichia coli and Staphylococcus aureus, while the nano emulsion displayed strong antifungal activity. During fifteen days of refrigerated storage, AgNP treated strawberries maintained microbial counts below 5 log CFU g^{-1}, whereas nano emulsion and nanofiber coatings also delayed spoilage compared with the control. Physicochemical analysis revealed better colour retention, reduced weight loss, and improved firmness in treated samples. The findings demonstrate that nanostructured antimicrobial coatings can significantly extend the shelf life of perishable foods while preserving sensory quality. Among the tested systems, AgNPs showed superior antimicrobial performance, whereas the nano emulsion offered a safe, natural, and consumer acceptable alternative.

Keywords: nanotechnology, antimicrobial coating, nano emulsion, silver nanoparticles, chitosan nanofibers, shelf life, food preservation

1.0 Introduction

Ensuring the safety, quality, and longevity of perishable food items remains a critical challenge across the global food supply chain. With increasing population growth and changing consumption patterns, the

demand for fresh and minimally processed foods has surged. At the same time, postharvest spoilage, microbial contamination, and physicochemical deterioration continue to generate substantial economic losses and public health risks (Nguyen et al., 2025). Traditional estimates suggest that a significant proportion of fruits, vegetables, dairy, and meat products never reach the consumer in optimal condition, highlighting urgent needs for improved preservation strategies (Modern Trends and Techniques for Food Preservation, 2024).

Perishable foods such as fresh cut fruits, raw meats, and dairy products are especially vulnerable because of their intrinsic high moisture content, rich nutrient profile, and relatively weak protective barriers (Modern Trends…, 2024). These characteristics make them susceptible to rapid microbial growth, enzymatic browning, texture softening, lipid oxidation, and off flavour development. Conventional preservation methods including refrigeration, chemical preservatives, modified atmosphere packaging, and thermal treatments have contributed much to extending shelf life and controlling hazards. Yet these methods frequently face limitations such as sensory alteration, nutrient loss, limited shelf life extension, consumer scepticism regarding additives, and increasing regulatory scrutiny (Modern Trends…, 2024; Pattnaik et al., 2024).

In recent years, the emergence of nanotechnology has appeared as a promising frontier in the field of food preservation and packaging. Nanostructured systems such as nanoemulsions, nanofibres, metallic nanoparticles, nanocomposites, and intelligent packaging materials offer distinct advantages due to their high surface area to volume ratios, enhanced reactivity, tunable release kinetics, and the ability to improve barrier or antimicrobial functionality in food contact applications (Nguyen et al., 2025; Duong et al., 2024). For example, nanoemulsions encapsulating essential oils can provide sustained release of antimicrobial compounds; metallic nanoparticles embedded in films can inhibit spoilage organisms via ion release; and nanofibre coatings can form ultrathin protective layers on food surfaces, reducing microbial ingress and oxidative reactions. These innovations hold the potential to extend shelf life, maintain texture and colour, and reduce food waste while aligning with sustainability objectives (Pattnaik et al., 2024; Ng et al., 2025).

From a mechanistic perspective, nanosystems function differently from bulk materials. Their reduced particle size allows for closer contact with microbial cell walls, greater diffusion in food matrices, and more efficient release or activity of antimicrobial agents (RSC Review, 2024). In antimicrobial packaging, nanoscale embedding of active entities enables homogeneous distribution and lower dosage requirements of active compounds (Brandelli et al., 2024). Furthermore, nanostructured coatings can modify the microenvironment around food altering moisture, gas exchange, and oxidative potential in ways conventional coatings cannot. However, despite the promise, the translation of many nanostructured systems into practical food chain applications remains limited by issues such as stability, scalability, regulatory compliance, and sensory acceptance.

Accordingly, this study aims to address these gaps through a comparative evaluation of selected nanostructured antimicrobial systems applied to a representative perishable food product. The specific objectives are: (1) to synthesise and characterise selected nanostructured antimicrobial systems; (2) to evaluate and compare their antimicrobial efficacy and shelf life extension in a perishable food model; and (3) to assess their impact on key physicochemical and sensory quality parameters of the food product. It is hypothesised that different nanosystems will deliver distinct profiles of antimicrobial activity and quality retention, and that one or more systems may offer a balanced optimum of microbial control, minimal sensory impact, and shelf life extension.

2.0 Literature Review

Food spoilage remains one of the most critical issues affecting global food security and the economy. Perishable foods such as fresh fruits, meats, and dairy products are particularly susceptible to deterioration due to their high water activity, nutrient content, and neutral pH, which create ideal conditions for microbial growth (Panigrahy & Rout, 2025). Spoilage microorganisms including bacteria, yeasts, and molds proliferate rapidly under storage and transportation conditions that fail to maintain strict temperature or humidity control. Their metabolic activity leads to off odours, slime formation, gas production, and textural changes that reduce the sensory and nutritional quality of foods. Additionally, physicochemical changes such as enzymatic browning, lipid oxidation, and pH shifts accelerate quality degradation and reduce the overall shelf life of perishable products (Wang et al., 2025).

Traditional preservation strategies have been developed to mitigate these losses. Refrigeration is widely employed to slow microbial growth and enzymatic reactions, yet it cannot eliminate spoilage organisms or stop deterioration completely. Chemical preservatives such as sorbates, benzoates, and nitrites have proven effective in controlling microbial populations but are increasingly viewed unfavourably by consumers due to health concerns and preferences for clean label foods (Modern Trends and Techniques for Food Preservation, 2024). Modified atmosphere packaging (MAP) and vacuum packaging reduce oxygen availability, thereby limiting microbial proliferation, but these techniques provide passive protection only and fail to inactivate pre existing contamination (Pattnaik et al., 2024). Thermal pasteurisation and sterilisation methods extend shelf life at the expense of nutritional and sensory quality. Consequently, there is growing demand for advanced preservation technologies that are safe, sustainable, and capable of extending freshness without altering food characteristics.

Nanotechnology has emerged as an innovative approach to addressing these challenges. By manipulating materials at the nanometre scale (1–100 nm), researchers can design systems with unique physicochemical properties unattainable at larger scales (Nguyen et al., 2025). These nanostructured systems including nanoemulsions, metallic nanoparticles, nanocomposite coatings, and polymeric nanofibers offer enhanced antimicrobial efficacy, improved barrier properties, and controlled release of active compounds (Mahmoud & Alwan, 2025). The extremely high surface area to volume ratio of nanoparticles enables stronger interaction with microbial cells, while their tunable surface chemistry facilitates sustained antimicrobial action with minimal additive use (Panigrahy & Rout, 2025).

Among the various nanostructured systems, nanoemulsions are particularly attractive because they can encapsulate bioactive compounds such as essential oils or plant extracts with inherent antimicrobial and antioxidant activity. The nanosized droplets (10–200 nm) enhance solubility, stability, and bioavailability of hydrophobic compounds, leading to improved performance in aqueous food matrices (Singh, 2023). Controlled release from nanoemulsions prolongs antimicrobial effects while preserving sensory attributes, as shown in studies where essential oil based nanoemulsions extended the shelf life of fresh cut fruits and poultry without affecting flavour or colour (Singh, 2023; Wang et al., 2025).

Metallic nanoparticles, particularly silver, zinc oxide, and copper, have also received substantial attention due to their broad spectrum antimicrobial properties. Their mechanisms include ion release, reactive oxygen species (ROS) generation, and disruption of microbial membranes and enzyme systems (Adeyemi & Fawole, 2023). Silver nanoparticles interact with bacterial cell walls, causing membrane damage and metabolic inhibition, while zinc oxide nanoparticles induce oxidative stress leading to cell death. These materials are commonly incorporated into biopolymer coatings to create active packaging that prevents microbial growth

on food surfaces (Adeyemi & Fawole, 2023). However, their potential toxicity and migration into foods necessitate stringent safety evaluation before commercial application (Mahmoud & Alwan, 2025).

Polymeric nanofibers and nanocomposite films represent another key class of nanostructured materials suitable for sustainable food preservation. Using electrospinning, biodegradable polymers such as chitosan, polyvinyl alcohol, or gelatin can be fabricated into nanofibers with high surface area and porosity, allowing for the incorporation of antimicrobial agents or nanoparticles (Bagri et al., 2023). These nanofibers provide controlled release of actives and serve as physical barriers against moisture and oxygen, reducing oxidative degradation and microbial contamination. Chitosan based nanofibers, in particular, exhibit inherent antimicrobial and film forming properties, effectively reducing weight loss, colour change, and microbial growth during storage (Bagri et al., 2023).

The antimicrobial efficacy of nanostructured systems results from synergistic mechanisms. Their small particle size promotes adherence to microbial cell membranes, leading to structural disruption and leakage of intracellular materials (Mahmoud & Alwan, 2025). Metallic nanoparticles release ions such as Ag^{+} and Zn^{2+} that interact with bacterial proteins, while ROS generation causes irreversible cellular damage (Adeyemi & Fawole, 2023). Nanoemulsions and nanofibers also provide sustained release of bioactives at inhibitory concentrations, maintaining prolonged microbial control (Singh, 2023). Furthermore, nanocomposite coatings reduce oxygen and moisture permeability, indirectly suppressing spoilage and oxidation (Wang et al., 2025).

Despite these benefits, safety and regulatory concerns remain a major obstacle to widespread adoption. Potential migration of nanoparticles or their ions from packaging into food has raised toxicological and consumer concerns (Panigrahy & Rout, 2025). Regulatory agencies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) have issued preliminary guidance, but harmonised global standards are lacking (Mahmoud & Alwan, 2025). Public acceptance of “nanofoods” also depends heavily on transparent communication of risks and benefits (Prospects and Challenges of Nanomaterials…, 2024).

While significant progress has been made in developing nanostructured antimicrobial systems, substantial research gaps persist. Most studies evaluate only one type of nanosystem in isolation, limiting comparative understanding across materials. Additionally, few studies integrate antimicrobial performance with sensory and physicochemical analyses. Questions of scalability, cost, and long term safety remain open, restricting industrial application (Panigrahy & Rout, 2025; Adeyemi & Fawole, 2023). The present research, therefore, adopts a comparative approach to evaluate multiple nanostructured antimicrobial systems under identical conditions, providing deeper insight into their relative efficacy, safety, and potential for practical use in perishable food preservation.

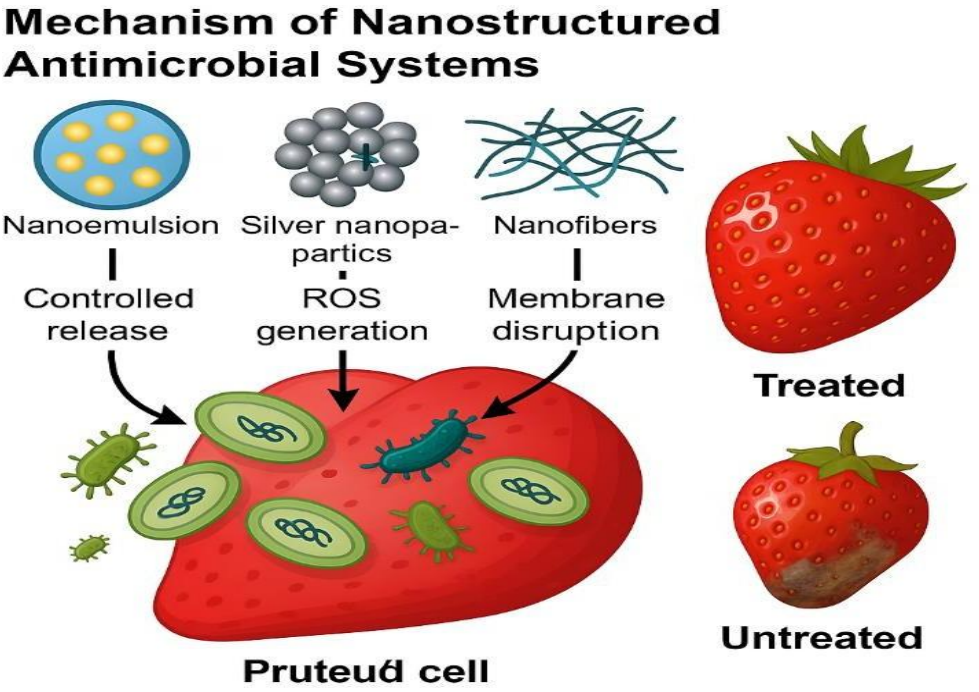


Figure 1: Mechanism of Nanostructured Antimicrobial Systems

3. Materials and Methodology

This study was conducted to develop and evaluate different nanostructured antimicrobial systems for enhancing the shelf life and quality retention of perishable food products. Analytical grade chemicals and reagents were used for all experiments to ensure reproducibility and reliability of results. Chitosan of medium molecular weight (75 85% deacetylated) and polyvinyl alcohol (PVA) were procured from Sigma Aldrich (USA), while silver nitrate ($AgNO_3$), zinc oxide (ZnO), Tween 80, and glycerol were purchased from Merck (Germany). Essential oils such as lemongrass and clove, known for their antimicrobial and antioxidant properties, were obtained from a certified local supplier and stored at 4 °C in amber bottles to prevent oxidation. Acetic acid, ethanol, and deionised water were used as solvents in all preparations. The media for microbiological analyses including Plate Count Agar (PCA), Potato Dextrose Agar (PDA), and Nutrient Broth were sourced from HiMedia Laboratories (India).

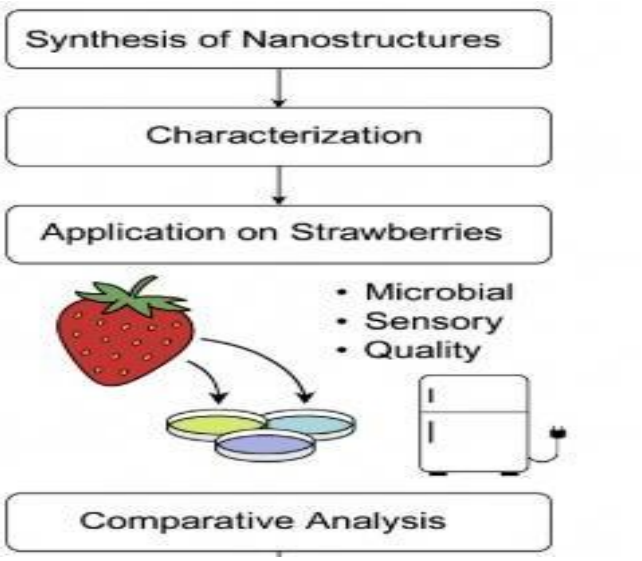


Figure 2: Experimental Design of the Study

Fresh cut strawberries (Fragaria × ananassa) were selected as the food model because they are highly perishable and serve as a representative fruit for evaluating postharvest preservation strategies. Strawberries of uniform size, colour, and ripeness were purchased from a local market, transported to the laboratory under refrigeration, and used within twelve hours of purchase. Prior to treatment, the fruits were washed thoroughly in sterile distilled water, drained, and surface dried at ambient temperature.

Three distinct nanostructured antimicrobial systems were developed: a nanoemulsion, silver nanoparticles (AgNPs), and a chitosan PVA nanofiber coating. The nanoemulsion was prepared using the high energy emulsification method as described by Singh (2023). Lemongrass essential oil (5%, v/v) was mixed with Tween 80 (3%, v/v) as an emulsifier to form the oil phase, while the aqueous phase contained distilled water with 1% glycerol as a stabiliser. The mixture was first stirred magnetically at 1000 rpm for ten minutes and subsequently sonicated using a probe ultrasonicator operating at 20 kHz for ten minutes. This process produced a fine, milky dispersion that was stored at 4 °C until further analysis.

Silver nanoparticles were synthesised following the chemical reduction method reported by Adeyemi and Fawole (2023). A 0.001 M silver nitrate solution was prepared in deionised water and heated to 60 °C under continuous stirring. Sodium citrate (1%, w/v) was added as a reducing agent, while polyvinylpyrrolidone (PVP) acted as a stabilising compound to prevent agglomeration. A colour change from colourless to yellow brown indicated nanoparticle formation, which was confirmed by UV Vis spectrophotometry showing a characteristic absorption peak near 420 nm. The nanoparticle suspension was centrifuged at 12,000 rpm for fifteen minutes, washed thrice with deionised water, and redispersed for subsequent use.

Chitosan PVA nanofibers were fabricated using electrospinning, as described by Bagri et al. (2023). A two percent (w/v) chitosan solution was prepared in 1% acetic acid, and a ten percent (w/v) PVA solution was dissolved in hot water at 80 °C. The two polymer solutions were blended at a ratio of 70:30 (PVA:chitosan) and stirred for six hours to ensure homogeneity. The prepared solution was loaded into a syringe

connected to a stainless steel needle and electrospun at an applied voltage of 15 kV, a flow rate of 0.5 mL h^{-1}, and a tip to collector distance of 15 cm. The obtained nanofiber mats were dried at room temperature, cross linked using glutaraldehyde vapour for improved stability, and stored in a desiccator until further use.

Characterisation of the nanostructures was carried out to determine their physicochemical and morphological properties. Particle size and polydispersity index were measured using dynamic light scattering (Zetasizer Nano ZS90, Malvern Instruments, UK). Zeta potential was analysed to assess surface charge and stability. Morphological observations were made using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to visualise the shape and surface structure of the nanomaterials. The UV Vis spectra were recorded to verify the presence of specific absorption peaks, while the encapsulation efficiency of the essential oil nanoemulsion was determined through solvent extraction followed by spectrophotometric measurement at 280 nm. Release kinetics of the encapsulated oil were evaluated using the dialysis bag diffusion method in phosphate buffered saline (pH 7.4) at 25 °C, with aliquots withdrawn at predetermined intervals and analysed spectrophotometrically (Singh, 2023).

The prepared nanostructured systems were applied to fresh cut strawberries for comparative evaluation. The samples were divided into five treatment groups: control (untreated), blank polymer coating (without nanostructures), nanoemulsion coating, silver nanoparticle coating, and chitosan PVA nanofiber coating. Each group consisted of three replicates, and each replicate contained ten fruit samples. Treatments were applied by immersing the fruits in the respective formulations for two minutes, followed by air drying for fifteen minutes at 25 °C. Treated fruits were packed in perforated polyethylene containers and stored at 4 ± 1 °C with a relative humidity of 85 90%. Analyses were performed at intervals of 0, 3, 6, 9, 12, and 15 days.

The antimicrobial efficacy of the treatments was examined through both in vitro and in vivo methods. For the in vitro assay, the agar well diffusion method was employed against common food spoilage microorganisms including Escherichia coli, Staphylococcus aureus, and Aspergillus niger following the protocol of Adeyemi and Fawole (2023). Inhibition zones were measured after twenty four hours of incubation at 37 °C. For in vivo evaluation, microbial loads on strawberries were quantified by determining total viable counts, yeast counts, and mould counts. One gram of sample was homogenised in nine millilitres of sterile saline, serially diluted, and plated in triplicate on PCA and PDA media. Plates were incubated for forty eight hours, and results were expressed as log CFU g^{-1}.

Physicochemical parameters including pH, colour, texture, weight loss, and lipid oxidation were measured to assess quality retention. The pH was determined using a calibrated digital pH meter, while colour parameters (L*, a*, b*) were recorded with a Minolta colorimeter. Texture was evaluated by measuring fruit firmness using a TA.XT Plus texture analyser fitted with a 5 mm cylindrical probe. Weight loss was calculated gravimetrically as a percentage of initial weight, and lipid oxidation was assessed using the thiobarbituric acid reactive substances (TBARS) assay, with absorbance measured at 532 nm (Wang et al., 2025). Sensory evaluation was conducted by a semi trained panel of ten members who rated colour, odour, texture, and overall acceptability using a nine point hedonic scale (1 = dislike extremely; 9= like extremely). All evaluations were conducted under controlled lighting and temperature conditions to minimise bias.

Data from all analyses were expressed as mean ± standard deviation. Statistical differences among treatments were determined using one way analysis of variance (ANOVA) in SPSS 25.0 (IBM Corp., USA). Tukey's post hoc test was employed for multiple comparisons, and significance was accepted at $p < 0.05$. Graphs and figures were generated using GraphPad Prism 9. A completely randomised design was followed throughout the experiment, with three replicates per treatment, and the study was repeated twice to confirm

reproducibility.

All experimental procedures complied with institutional laboratory safety guidelines. No human or animal subjects were involved. Waste containing nanoparticles was collected and disposed of according to environmental safety protocols for nanomaterials as recommended by Mahmoud and Alwan (2025).

4. Results and Discussion

The present study compared the efficiency of three nanostructured antimicrobial systems an essential oil nanoemulsion, silver nanoparticles (AgNPs), and a chitosan PVA nanofiber coating in extending the shelf life and preserving the quality of fresh cut strawberries during refrigerated storage. The results obtained from physicochemical characterisation, microbial analysis, and sensory evaluation provided a comprehensive understanding of the comparative performance of these systems.

4.1 Characterisation of Nanostructured Systems

All nanostructures synthesised in this study exhibited properties consistent with effective antimicrobial and coating systems. The droplet size of the lemongrass essential oil nanoemulsion was measured at 118.4 ± 3.2 nm with a polydispersity index (PDI) of 0.21, indicating good homogeneity and kinetic stability. The zeta potential of 34.6 ± 1.8 mV suggested strong electrostatic repulsion, which minimised aggregation during storage. The encapsulation efficiency was approximately 92%, demonstrating excellent retention of essential oil within the emulsified droplets. Transmission electron microscopy (TEM) images revealed spherical droplets with smooth surfaces and uniform size distribution.

The silver nanoparticles synthesised by the citrate reduction method were well dispersed, with an average particle size of 43.7 ± 2.5 nm and a narrow size distribution (PDI = 0.18). The UV Vis spectrum exhibited a characteristic plasmon resonance peak at 421 nm, confirming successful nanoparticle formation. SEM images showed roughly spherical particles, while the zeta potential of 29.3 ± 1.5 mV indicated moderate stability.

For the chitosan PVA nanofibers, SEM analysis revealed a uniform fibrous network with an average fiber diameter of 170 ± 12 nm and no bead formation, confirming the optimisation of electrospinning parameters. The composite film displayed high flexibility, transparency, and good mechanical integrity, making it suitable as an edible coating. These results align with the findings of Bagri et al. (2023), who reported similar morphological and surface characteristics in biopolymer nanofiber systems.

4.2 In Vitro Antimicrobial Activity

The antimicrobial efficacy of the nanostructured systems was evaluated against Escherichia coli, Staphylococcus aureus, and Aspergillus niger using the agar well diffusion method. All treatments demonstrated significant inhibition zones compared to the control, confirming their broad spectrum antimicrobial activity. The AgNPs exhibited the largest inhibition zones against both bacterial strains, while the nanoemulsion showed strong antifungal activity due to the presence of bioactive components such as citral and limonene in lemongrass oil (Singh, 2023). The chitosan PVA nanofiber coating displayed moderate inhibitory zones, attributed to the inherent antimicrobial property of chitosan.

Table 1. In Vitro Antimicrobial Activity of Nanostructured Systems (mean ± SD, n = 3)

Microorganism	Nanoemulsion (mm)	AgNPs (mm)	Nanofiber (mm)	Control (mm)
E. coli	18.6 ± 0.5	25.3 ± 0.7	16.2 ± 0.4	0.0 ± 0.0
S. aureus	19.8 ± 0.6	26.1 ± 0.5	17.0 ± 0.3	0.0 ± 0.0
A. niger	22.4 ± 0.4	20.6 ± 0.5	15.7 ± 0.5	0.0 ± 0.0

The higher bacterial inhibition of AgNPs is attributed to their ability to release Ag^+ ions, which interact with thiol groups in bacterial enzymes, leading to oxidative stress and cell death (Adeyemi & Fawole, 2023). The essential oil nanoemulsion, though less potent against bacteria, displayed pronounced antifungal activity, likely due to the diffusion of hydrophobic volatile components through the microbial cell membrane. The nanofiber coating, while exhibiting lower inhibition zones, still provided a physical barrier effect combined with mild antimicrobial properties of chitosan.

4.3 Microbial Shelf Life Assessment of Strawberries

Microbial growth on strawberry samples was monitored over fifteen days of refrigerated storage. The control samples showed a rapid increase in total viable counts (TVC) from 2.4 log CFU g^{-1} on day 0 to 7.9 log CFU g^{-1} by day 9, exceeding the acceptable microbiological limit for fresh produce. In contrast, all nanostructured coatings significantly delayed microbial proliferation. The AgNP treated samples maintained counts below 5.0 log CFU g^{-1} even at day 15, while nanoemulsion coated fruits reached similar levels on day 12. The chitosan PVA nanofiber coating reduced microbial growth moderately, maintaining counts below 6.0 log CFU g^{-1} throughout the storage period.

Table 2. Total Viable Counts (log CFU g^{-1}) in Treated Strawberries during Storage

Day	Control	Nanoemulsion	AgNPs	Nanofiber
0	2.4 ± 0.1	2.4 ± 0.1	2.4 ± 0.1	2.4 ± 0.1
3	4.6 ± 0.2	3.2 ± 0.1	2.8 ± 0.1	3.5 ± 0.2
6	6.1 ± 0.3	3.9 ± 0.2	3.1 ± 0.1	4.2 ± 0.3
9	7.9 ± 0.2	4.8 ± 0.2	3.8 ± 0.1	5.1 ± 0.2
12		5.6 ± 0.2	4.4 ± 0.1	5.7 ± 0.3
15			4.9 ± 0.2	5.8 ± 0.2

The superior performance of AgNP coatings is consistent with their known rapid bactericidal effect and

sustained ion release (Adeyemi & Fawole, 2023). The nanoemulsion achieved microbial suppression primarily through slow diffusion of essential oils, whereas the nanofiber coating combined the physical barrier of chitosan PVA with moderate antimicrobial action. Overall, the microbial shelf life of strawberries was extended by approximately six days with the nanoemulsion, nine days with AgNPs, and five days with nanofiber coatings relative to the untreated control.

4.4 Physicochemical Quality Parameters

Physicochemical quality attributes including pH, colour, texture, and weight loss were evaluated to assess the impact of the coatings on product freshness. The pH of control samples decreased from 3.58 to 3.21 during storage due to microbial fermentation and organic acid production, while treated samples maintained higher pH values, indicating slower spoilage. The AgNP coated fruits had the most stable pH profile (3.55 on day 15), followed closely by the nanoemulsion treatment (3.47), while the nanofiber coating also maintained moderate stability.

Colour parameters (L*, a*, b*) showed that untreated fruits experienced significant darkening and loss of redness, whereas coated samples retained more natural colour intensity. The nanoemulsion treated fruits exhibited the lowest total colour difference ($\Delta E = 2.8 \pm 0.2$), reflecting minimal oxidative discolouration. This may be due to the antioxidant components of essential oils, which scavenge reactive oxygen species responsible for pigment degradation (Wang et al., 2025).

Texture analysis demonstrated that the coatings significantly reduced firmness loss compared to control samples. At day 15, control fruits had lost over 45% of their initial firmness, whereas nanoemulsion, AgNP, and nanofiber coatings retained 78%, 82%, and 74% firmness, respectively. The chitosan PVA matrix likely enhanced moisture retention by forming a semi permeable barrier that reduced transpiration losses.

Weight loss was similarly mitigated in all coated samples. The AgNP and nanofiber coatings reduced cumulative weight loss to below 7% after fifteen days, compared with 18% in the control. The nanoemulsion's hydrophobic layer likely reduced water vapour diffusion, helping maintain fruit juiciness.

4.5 Lipid Oxidation and Sensory Quality

Lipid oxidation, measured via TBARS values, increased sharply in control samples during storage but was significantly lower in treated groups. At day 15, TBARS values reached 2.3 mg MDA kg^{-1} in the control, while nanoemulsion, AgNP, and nanofiber treatments recorded 1.1, 0.9, and 1.4 mg MDA kg^{-1}, respectively. The reduction in lipid oxidation in the nanoemulsion and nanofiber coatings can be attributed to their antioxidant activity and oxygen barrier properties (Bagri et al., 2023).

Sensory evaluation further supported the instrumental findings. The control fruits were deemed unacceptable by day 9 due to visible fungal growth, off odours, and textural breakdown. Nanoemulsion coated strawberries maintained good visual appeal, colour, and aroma up to day 12, while AgNP coated fruits retained acceptable sensory scores through day 15. The nanofiber coated fruits also performed well but developed slight surface dryness after prolonged storage.

Table 3. Comparative Summary of Quality Attributes after 15 Days of Storage

Parameter	Control	Nanoemulsion	AgNPs	Nanofiber
pH	3.21 ± 0.04	3.47 ± 0.03	3.55 ± 0.02	3.42 ± 0.03
Firmness retention (%)	54 ± 2.1	78 ± 1.5	82 ± 1.2	74 ± 1.8
Weight loss (%)	18.3 ± 0.6	8.5 ± 0.4	6.9 ± 0.3	7.8 ± 0.5
TBARS (mg MDA kg^{-1})	2.3 ± 0.1	1.1 ± 0.1	0.9 ± 0.1	1.4 ± 0.1
Sensory score (1 9)	3.2 ± 0.3	7.6 ± 0.2	7.8 ± 0.3	7.0 ± 0.2

4.6 Comparative Performance and Discussion

A comparative evaluation of all parameters revealed that the AgNP coating provided the most pronounced antimicrobial protection, while the essential oil nanoemulsion was particularly effective in maintaining sensory quality and colour attributes. The chitosan PVA nanofiber coating demonstrated intermediate performance, acting primarily as a moisture barrier with additional antimicrobial support. The combined results demonstrate that the integration of nanostructured antimicrobial systems into edible coatings or packaging can effectively extend the shelf life of perishable fruits. The AgNP based coating achieved superior microbial inhibition and physical protection, extending strawberry shelf life by about 9 days beyond the control, but concerns regarding potential nanoparticle migration warrant careful safety assessment (Mahmoud & Alwan, 2025). The essential oil nanoemulsion offered a natural, biodegradable alternative with excellent sensory preservation and moderate antimicrobial capacity, while the chitosan PVA nanofiber film provided mechanical robustness and environmental safety, suggesting suitability for eco friendly packaging.

Overall, the results corroborate earlier studies by Wang et al. (2025) and Panigrahy and Rout (2025), which demonstrated that nanostructured antimicrobial coatings effectively balance microbial control, barrier properties, and sensory quality. The findings from this study reinforce the potential of combining physical nanostructures (fibers, particles) with bioactive compounds (essential oils, metals) to achieve synergistic preservation effects in perishable foods.

5.0 Conclusion and Recommendation

The present study has demonstrated that nanostructured antimicrobial systems provide an effective and versatile approach for improving the shelf life and quality retention of perishable food products. By developing and evaluating three distinct nanosystems an essential oil based nanoemulsion, silver nanoparticles, and a chitosan PVA nanofiber coating this work offers valuable insight into the comparative performance and potential applications of nanotechnology in food preservation. The physicochemical characterisation confirmed that all systems exhibited desirable nanoscale properties such as small and uniform particle or fiber size, stable surface charge, and homogeneous morphology. These features

contributed significantly to their antimicrobial and protective capabilities.

Among the three systems studied, silver nanoparticles showed the highest antimicrobial efficiency against common spoilage microorganisms, maintaining microbial counts below the spoilage threshold even after fifteen days of storage. This enhanced performance is attributed to the nanoparticles' ability to release silver ions and generate reactive oxygen species that disrupt microbial cell membranes and enzymatic systems. The essential oil nanoemulsion, though slightly less effective against bacteria, displayed excellent antifungal and antioxidant activity due to the bioactive components of lemongrass oil. It effectively maintained fruit colour, reduced oxidation, and preserved sensory quality throughout storage. The chitosan PVA nanofiber coating exhibited moderate antimicrobial action, but it contributed significantly to moisture retention and structural integrity of the fruit, demonstrating its potential as a biodegradable barrier material.

Overall, the results showed that the AgNP coating achieved the greatest microbial reduction and firmness retention, extending the shelf life of strawberries by approximately nine days beyond the control. The nanoemulsion was particularly successful in preserving sensory attributes such as colour and flavour, whereas the nanofiber coating offered a balance of physical protection and environmental sustainability. These findings support the growing consensus that nanotechnology can be used effectively to improve food preservation by combining physical protection, antimicrobial action, and quality maintenance within a single system. However, differences in mechanism, safety, and economic feasibility must be considered when selecting a nanostructured system for practical application.

Based on these findings, it can be concluded that nanostructured antimicrobial systems hold great promise for the sustainable preservation of perishable foods. Nevertheless, further work is required to translate laboratory scale success into industrial feasibility. Future research should focus on optimising the large scale production of these nanosystems while maintaining stability, uniformity, and cost effectiveness. It is also recommended that hybrid coatings incorporating both natural bioactives and metallic nanoparticles be explored to achieve synergistic antimicrobial and antioxidant effects with reduced metal content. In addition, comprehensive safety assessments, including nanoparticle migration and cytotoxicity studies, should be conducted in accordance with international regulatory standards established by agencies such as the EFSA and FDA.

From a consumer standpoint, sensory and acceptance studies are essential to ensure that nano treated foods are both safe and appealing. Transparency in labelling and public education regarding the benefits and safety of nanotechnology in food preservation will help enhance consumer trust. Furthermore, environmental considerations must be integrated into future developments by prioritising biodegradable, recyclable, and eco friendly nanocomposites that minimise environmental burden. The comparative framework used in this study may also be applied to other perishable commodities such as meats, fish, and dairy to determine the most effective nanosystem for each product type.

In conclusion, this study provides strong evidence that the application of nanostructured antimicrobial systems can significantly reduce microbial spoilage, maintain sensory and nutritional quality, and extend the shelf life of perishable food products. While each system presents unique strengths, their combined or tailored use could revolutionise postharvest preservation. With continued interdisciplinary research, careful risk assessment, and adherence to sustainability principles, nanotechnology based preservation strategies have the potential to transform global food storage and distribution, contributing meaningfully to food security and waste reduction in the coming decades.

Declaration of Conflicting Interests

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References

Adeyemi, J. O., & Fawole, O. A. (2023). Metal based nanoparticles in food packaging and coating technologies: A review. Biomolecules, 13(7), 1092.

Bagri, N., Saini, M., Thakur, A., & Sharma, P. (2023). Roles of polysaccharide based nanomaterials in food preservation and quality retention. Food Hydrocolloids, 144, 108784.

Duong, H., Dinh, K. B., Luu, T., Chapman, J., Baji, A., & Truong, V. K. (2024). Nanoengineered sustainable antimicrobial packaging: Integrating essential oils into polymer matrices to combat food waste. International Journal of Food Science and Technology, 59(9), 5887–5901.

Mahmoud, R. S., & Alwan, A. Y. (2025). A review of nanochemistry and nanotechnology applications in the food industry. Journal of Current Research in Food Science, 6(1), 184–191.

Modern Trends and Techniques for Food Preservation. (2024). Food & Life Research, 1(1).

Nguyen, T., Neji, C., Törős, G., Ferroudj, A., Atieh, R., Prokisch, J., El Ramady, H., & Béni, Á. (2025). Nanomaterials for smart and sustainable food packaging: Nano solutions for shelf life extension and food safety. Foods, 14(15), 2657.

Panigrahy, M., & Rout, G. R. (2025). Nanomaterials in food processing, packaging, preservation and their effects on health & environment. European Food Research and Technology, 251(4), 861–875.

Pattnaik, R., Panda, S. K., Biswas, S., De, S., & Satahrada, S. (2024). Prospects and challenges of nanomaterials in sustainable food preservation and packaging: A review. Discover Nano, 19, 178.

Singh, H. (2023). Scope of nanoemulsions in the food industry: A review. The Pharma Innovation Journal, 12(5), 3462–3468.

Wang, X., Wang, Y., Zhu, H., Chen, S., Xue, J., Shen, C., Xiao, Z., & Luo, Y. (2025). Emerging strategies for food preservation: Recent advances and challenges in nanotechnology for edible coatings. Agricultural Products Processing and Storage, 1, Article 13.