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ARTICLE

Zein-Based Electrospun Composite Nanofiber Films for Food Packaging

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ABSTRACT: Food packaging films play a crucial role in maintaining food quality and safeguarding human health, making the development of advanced packaging materials an important research priority. Conventional petroleum-based plastic films suffer from poor degradability and may pose environmental and potential health concerns, while many currently available preservative films still exhibit limited freshness-retention performance. Therefore, the development of environmentally friendly, non-toxic, biodegradable, and efficient food-packaging materials is of great significance. In this study, coaxial electrospinning was employed to fabricate a core–shell nanofiber film by encapsulating resveratrol within gelatin/zein (GA/ZN) fibers, aiming to enhance the preservation performance of edible packaging films. The as-prepared films were systematically characterized in terms of morphology, wettability, and functional properties, followed by practical preservation tests using strawberries and bananas as model fruits. The results demonstrated that, compared with traditional plastic films, the incorporation of corn zein into gelatin-based nanofibers effectively extended the shelf life of the tested fruits by approximately 2–3 days at room temperature. In comparison with pure gelatin nanofibers, the average fiber diameter decreased from 1.67 to 0.91 μm, while the water contact angle increased to 105.2°, indicating enhanced hydrophobicity and improved barrier-related properties. The gelatin/zein-resveratrol nanofiber film exhibited 2,2-Diphenyl-1-picrylhydrazyl (DPPH) and 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) radical scavenging rates of 95.85 ± 0.11% and 94.90 ± 0.11%, respectively, and antibacterial rates of 91 ± 2% against *Staphylococcus aureus* (*S. aureus*) and 94 ± 1% against *Escherichia coli* (*E. coli*). These antioxidant and antibacterial properties contributed to delaying fruit deterioration and maintaining postharvest quality. Overall, this study provides a promising strategy for the design of edible, biodegradable, and bioactive nanofiber films and offers new insights into the development of sustainable active food-packaging materials for fresh-produce preservation.

KEYWORDS: Gelatin; zein; resveratrol; coaxial electrospinning; food preservation; nanofiber films; antimicrobial

1 Introduction

Food packaging plays an important role in the food industry. Modern food packaging not only needs to provide physical protection for food to prevent it from being damaged during long-distance transportation, but also needs to maintain the freshness of food, extend its shelf life, ensure the best taste of food, and facilitate consumers' daily use [1]. Most foods, such as fresh produce, dairy products, fruits and vegetables, due to their own characteristics, are prone to microbial infection in all aspects of raw material handling, processing, transportation and storage, which can lead to food spoilage and decay. Studies show that approximately one million tons of food worldwide have deteriorated due to improper packaging, transportation and storage, thereby reducing the commercial and edible value of food and even causing serious harm to human health [2,3]. Therefore, developing food packaging materials with excellent performance is an effective means to avoid food waste and ensure the health of customers' consumption. At present, the most commonly used traditional food packaging materials are petroleum-based plastics. Due to their advantages such as low cost, stable performance, good formability, good transparency and good wear resistance, they have become the first choice for food packaging materials [4]. However, the long-term and large-scale use of plastic has also caused serious pollution problems. Plastic pollution has seriously threatened the stability and health of the ecosystem and human beings [5–7]. Moreover, some studies have found that plastic pollution has spread to the North and South Poles [8]. In view of the harmfulness of petroleum-derived plastic products and the uncertainty of crude oil prices and reserves, researchers are urgently developing new types of green food packaging.

Green food packaging materials should be biodegradable, safe, and derived from renewable resources. Among them, protein-based materials are particularly attractive for sustainable packaging applications. Among them, gelatin and zein have received extensive attention because they have good film-forming ability, biocompatibility, non-toxicity, and biodegradability [9]. Gelatin is a hydrophilic protein with excellent film-forming properties, making it suitable for adding active compounds [10]. However, its relatively poor water resistance and mechanical stability limit its direct application in food packaging. In contrast, zein is a hydrophobic protein derived from corn, with good moisture-proof properties, which can improve the water resistance of composite materials [11]. Therefore, combining gelatin and zein is a reasonable approach that can integrate the advantages of these two materials, namely the film-forming ability of gelatin and the hydrophobicity of zein, thus providing a promising foundation for the development of functional food packaging films.

Electrospinning technology is a technique for producing polymer fibers by using an external electric field, which is characterized by low cost and high efficiency [12,13] The fibers produced by this method typically possess a high specific surface area, tunable pore size and porosity, and well-designed physicochemical functionalities, thereby offering significant advantages in structural regulation and performance optimization. More importantly, electrospinning is applicable to a wide range of material systems, including organic polymers, metal oxides, carbon-based materials, and their composites. In addition, it enables the construction of complex nanofibrous architectures, such as porous, core–shell, hollow, cross-linked, and hierarchical structures, which can endow the resulting materials with enhanced mechanical properties, chemical stability, and functional performance. Owing to these merits, electrospinning has become an important platform technology for the development of advanced nanofibrous materials and has shown broad application prospects in fields such as filtration, energy storage, and biomedical devices [14,15]. Furthermore, bubble electrospinning, as an needle-free electrospinning strategy, is regarded as a highly promising method for large-scale production of nanofiber films. This is because it can simultaneously generate multiple jet streams, and compared with the traditional single-needle electrospinning, it can enhance production efficiency. Recent research and reviews have highlighted its potential in scaling up production [16]. Compared with traditional materials, the polymer fibers obtained by electrospinning can achieve excellent control of air permeability and moisture permeability in terms of structure and properties, which is crucial for extending the shelf life and maintaining food quality [17]. This is because appropriate gas permeability helps regulate O_2/CO_2 exchange and suppress respiration, whereas suitable moisture permeability reduces excessive dehydration while avoiding moisture accumulation that may accelerate microbial spoilage [18]. However, there are still some problems with the use of nanofibers obtained by electrospinning in food packaging materials, such as inferior preservation effect compared to traditional cling films and limited mechanical properties [19,20]. Coaxial electrospinning is a versatile and efficient technique for fabricating functional nanofibers with complex architectures, particularly core–shell structures. By employing a dual-capillary nozzle system, this method enables the simultaneous incorporation of two different materials into a single fiber, with the inner nozzle delivering the core solution and the outer nozzle dispensing the shell solution. Such a unique configuration allows precise control over the spatial distribution of materials within the fiber, thereby facilitating the integration of distinct polymer properties and the tailoring of surface characteristics, structural stability, and functional performance [14]. Owing to these advantages, coaxial electrospinning has become an attractive strategy for the design of advanced nanofibrous materials for a wide range of applications. In coaxial electrospinning, continuous double-sheathed nanofibers are made from two materials during the spinning process, thus keeping the two materials immiscible. The packaging of coaxial nanofibers helps maintain the structural and functional stability of bioactive agents by minimizing the Coulomb stress applied during electrospinning. It is precisely because of coaxial electrospinning technology that the performance of the material can be greatly enhanced.

Resveratrol(R), as a phenolic compound present in many fruits and vegetables, has been proven to have great potential in anti-inflammation and the treatment of various human diseases (usually, arthritis [21], obesity [22], diabetes [23], cancer [24]). In fact, through further research, it was found that due to its antibacterial and antioxidant properties [25,26], researchers have attempted to use it for food preservation [10,25,26]. However, due to the poor solubility and stability of R itself [27], this greatly limits its application range. To overcome these problems, predecessors have conducted relevant research work, such as encapsulating R in emulsions [28], nanoparticles [29], films [30] and inclusion complexes [31].

Based on these considerations, resveratrol was encapsulated within gelatin/zein fibers in the present study to construct a biodegradable and bioactive nanofiber film with improved preservation performance for fresh produce. Through a series of characterizations of the nanofiber film, the properties of Gelatin/Zein-Resveratrol (GA/ZN-R) were evaluated. The practical preservation efficacy of this material was validated through fruit and vegetable storage tests using strawberries and bananas [32,33]. As shown in Fig. 1, it illustrates the preservation mechanism of gelatin fiber film with resveratrol added. These findings demonstrate that this nanofiber film offers a novel approach for edible, biodegradable, and functionally active food packaging, presenting potential industrial applications.

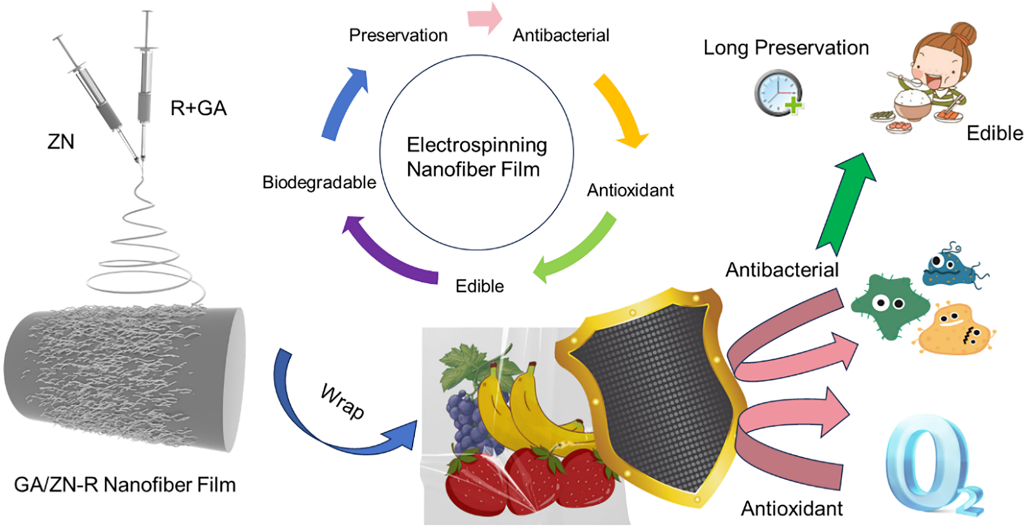

Figure 1: Freshness preservation mechanism of resveratrol-added gelatin-based fiber films.

2 Materials and Methods

2.1 Materials

Gelatin (Viscosity ≥ 15.0 $mm^2 \cdot s^{-1}$; Sinopharm Chemical Reagent Co.), Zein (N:13%; Tokyo Kasei Kogyo Co.), Resveratrol (99.0%; Shanghai McLean Biochemical Technology Co.), 2,2,2-Trifluoroethanol (99.5%, AR; Shanghai McLean Biotechnology Co.), Acetic acid (≥99.8%, AR; Taicang Shanghai Reagent Co.) were used as received, without any further purification. All chemicals were of analytical grade (AR). The solvents and reagents were used as provided by the suppliers, and no additional purification steps were applied.

2.2 Preparation of Zein-Based Electrospun Composite Nanofiber Films

For the preparation of the shell electrospinning solution, 3.0 g of zein was dissolved in 10 mL of acetic acid in a 20 mL glass vial to obtain a zein solution with a concentration of 30% w/v. For the preparation of the core electrospinning solution, 1.6 g of gelatin and 0.6 g of resveratrol were dissolved in 10 mL of trifluoroethanol, corresponding to 16% w/v gelatin and 6% w/v resveratrol, respectively. Therefore, the mass ratio of gelatin to resveratrol in the core solution was 8:3. During coaxial electrospinning, the shell and core solutions were delivered at flow rates of 1.1 and 0.4 mL/h, respectively. Based on the solid contents of the two spinning solutions and their flow rates, the theoretical solid composition of the final GA/ZN-R nanofiber film was approximately 79.0 wt% zein, 15.3 wt% gelatin, and 5.7 wt% resveratrol, assuming complete solvent evaporation and full retention of all solid components. Both solutions were stirred at room temperature using a magnetic stirrer at 500 rpm until complete dissolution. All procedures involving trifluoroethanol and acetic acid were performed in a fume hood, and laboratory personnel wore protective gloves and safety goggles throughout the operation.

To fabricate the nanofiber films, both coaxial and uniaxial electrospinning techniques were employed [34]. In the coaxial electrospinning process, gelatin and resveratrol served as the core (inner layer) materials, while zein functioned as the shell (outer layer) material. The outer solution, composed of zein was delivered at a flow rate of 1.1 mL/h, while the inner solution containing gelatin and resveratrol was supplied at a flow rate of 0.4 mL/h. The applied voltage was maintained at 8.0 kV, and the distance between the needle tip and the collector was set to 15 cm. Under these conditions, a stable Taylor cone was achieved, ensuring continuous and uniform fiber formation. The spinning time was precisely controlled to produce nanofiber films with the desired morphology. Following electrospinning, the gelatin-based nanofiber films were carefully removed from the aluminum foil collector and placed in a vacuum drying oven at 60°C for 24 h to eliminate residual solvents, resulting in dry, solvent-free nanofiber films. For comparison, uniaxial electrospinning was conducted using a single-spinning nozzle. Zein and gelatin solutions were electrospun individually. For the zein solution, the flow rate was set at 1.2 mL/h with an applied voltage of 15 kV. For the gelatin solution, the flow rate was adjusted to 1.0 mL/h, with an applied voltage of 7.9 kV. The resulting nanofiber films were also subjected to vacuum drying at 60°C for 24 h to remove any remaining solvents. The relevant experimental specific parameters are referred to in Table 1.

2.3 Characterization

2.3.1 Morphological and Molecular Structure Characterization

The surface and cross-sectional morphology of nanofiber films was observed using a Scanning Electron Microscope (SEM, Quanta FEG, FEI Company of USA) after sputtering with gold for 60 s. ImageJ software (National Institutes of Health, Bethesda, Maryland, USA) was used to measure the pore size distribution on the surface of nanofibers. Approximately 100 measurements (i.e., a measure of the fiber diameter) per sample were performed [35].

Table 1: Experimental specific parameters.

Type	Parameter	Note/Range of Key Optimization Parameters
Sample composition	Out layer: Zein, 3.0 g, Inner layer: Gelatin: 1.6 g, Resveratrol: 0.6 g, Mass ratios of samples: zein: gelatin: resveratrol = 15:8:3	——
Solution concentration	Outer layer: Zein—30% w/v, Inner layer:Gelatin—16% w/v, Resveratrol—6% w/v	——
Solvent	Acetic acid solution: 10 mL, Trifluoroethanol: 10 mL	——
Inner and outer flow rate	Inner flow rate: 0.4 mL/h, Outer flow rate: 1.1 mL/h	Inner flow rate: 0.2~0.6 mL/h, Outer flow rate: 0.8~1.4 mL/h
Voltage	8.0 kV	7~15 kV
Receiving distance	15 cm	——
Environmental condition	Room temperature (25 ± 1°C)	——
Solution stirring time	2 h	——
Humidity	50 ± 5%	——
Electrospinning time	30 min	——
Collector type	Aluminum foil sheet	——
Film thickness	80–100 μm	——

The molecular structures of GA/ZN-R, Zein (ZN), and Gelatin (GA) were determined by Fourier transform infrared spectroscopy (FT-IR, SPECTRUM100, Perkin Elmer Company of USA). These determinations were carried out on an infrared spectrometer, with the scanning spectral range being from 0 to 4000 cm^{-1}.

2.3.2 Water Contact Angle (WCA)

A square-shaped nanofiber thin film is cut and fixed onto a glass slide. The automatic titration method is employed, and a contact angle/surface tension measuring instrument (DSA30, KRüSS GmbH Germany) is used to measure the contact angle of water on the fiber film. The volume of the water droplets falling on the surface of the fiber film is 5 μL. The contact angle is measured by capturing the image at the moment when the droplet first comes into contact with the sample. Each sample undergoes three consecutive measurements to ensure accuracy [36].

2.3.3 Evaluation of Preservation Performance

To evaluate the preservation performance of nanofiber films, preservation performance tests were conducted using two representative fruits: strawberries from Dandong Liaoning (with a short preservation period) and bananas from Guangxi (ripening fruits). Fresh strawberries and bananas were purchased from the market and hand-picked to ensure uniform size and no visible defects. For each processing, 100.0 ± 15.0 g of strawberries and 100.0 ± 15.0 g of bananas were placed in 1.8 L food-grade polypropylene (PP) containers (dimensions: 20 cm × 12 cm × 5 cm), and at each of the four corners of the container, a hole of approximately 2 cm^2 was created using scissors, respectively, sealed with (i) no wrapping (Blank Control), (ii) commercial plastic film cling film, and (iii) the prepared nanofiber film cling film [33]. All storage tests were conducted at 20 ± 0.5°C, and morphological changes were recorded daily. All assays were performed in triplicate.

2.3.4 Assessment of Weight and Weight Loss Rate of Fruits

Each sample group was divided into three independent test groups and conducted simultaneously. The weight of the test fruits was measured once a day, and the average value was calculated and recorded. The weight loss rate of bananas was calculated once every three days, and the weight loss rate of strawberries was calculated once every two days. The weight loss rate was determined using the following formula [37], sample size n = 3:

$$WL = \frac{(M_0 - M_1)}{M_0} \times 100\%$$

where M_0 is the initial weight (g) of the fruits and M_1 is the final weight (g) of the fruits.

2.3.5 Determination of Total Soluble Solid Content (TSS) during Fruit Storage

The fruit juice is extracted and filtered through a blender to obtain the juice, and then it is dripped onto a refractometer (PR-1 Haenel Instrument A630, Shanghai, China) for measuring the soluble solid content. The range is 0–60 °Brix, with an accuracy of ±0.1 °Brix [38], sample size n = 5.

2.3.6 Antioxidant and Antibacterial Tests

To evaluate the antioxidant activity of the nanofiber films, 2,2-Diphenyl-1-picrylhydrazyl (DPPH) and 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) radical scavenging assays were conducted. For the DPPH assay, a fresh 0.1 mM DPPH solution in ethanol was prepared. The nanofiber films (25 mg) were immersed in 5 mL of the DPPH solution and incubated under dark conditions at 25°C for 30 min. Absorbance at 517 nm was recorded using a UV-Vis spectrophotometer (Shimadzu Corporation, Japan). and absorbance changes were used to assess the radical scavenging activity before and after sample immersion (n = 3).

For the ABTS assay, the solution was prepared by combining ABTS (7 mM) and potassium persulfate (2.4 mM) in a l:0.5 volume ratio, then incubated in the dark for 12–16 h. Distilled water was added to adjust the absorbance to 0.6 (±0.1) at 734 nm. Approximately 25 mg of the film was immersed in 5 mL of the ABTS solution and incubated in the dark for 30 min. After incubation, the nanofiber films were removed, and the absorbance of the ABTS solution was recorded. Pure ABTS solution was used as a control, and radical scavenging activity was assessed by the change in absorbance at 734 nm (n = 3). The antioxidant activity of the films was calculated using the following formula:

$$Antioxidant\ acitivity\,(\%) = \frac{A_i - A_f}{A_i} \times 100\%$$

where, A_i refers to the absorbance of the untreated DPPH or ABTS solution, while A_f refers to the absorbance of the untreated DPPH or ABTS solution.

The antibacterial performance of all samples was evaluated using the agar diffusion method. For both *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*), 4 mg of each sample was first sterilized by ultraviolet irradiation. The sterilized samples were then introduced into Eppendorf tubes containing bacterial suspensions and Luria–Bertani (LB) medium, followed by incubation at 37°C for 8 h. Subsequently, the suspensions were spread onto agar plates and further incubated at 37°C for 12 h to observe and quantify bacterial colony formation. All assays were performed in triplicate. Antibacterial efficiency was calculated according to the following formula:

$$Antibacterial\,ratio\,(\%) = \frac{N_c - N_S}{N_C} \times 100\%$$

where N_c refers to the colony count for the control group, while N_s corresponds to that for the sample group on nutrient agar plates.

3 Results and Discussion

3.1 Characterization of Nanofiber Film

The FT-IR spectra Fig. 2 of the composite nanofiber films revealed characteristic absorption peaks indicative of protein-based materials, with notable variations in peak intensities and slight shifts in peak positions, reflecting compositional differences and intermolecular interactions within the matrix. A broad and intense absorption band observed in the region of 3300–3400 cm^{-1} corresponds to the N-H stretching vibrations [10], typically associated with hydrogen bonding. This feature is characteristic of proteinaceous materials such as gelatin and zein, both of which possess amino groups capable of forming extensive hydrogen bonding networks. The presence of this peak suggests strong intermolecular interactions and confirms the integration of hydrogen bonds within the composite structure. In the region of 2800–3100 cm^{-1}, a well-defined peak attributed to the C-H stretching vibrations of aliphatic groups ($-CH_2$ and $-CH_3$) was observed [11]. Specifically, a more distinct absorption between 2880–3000 cm^{-1} indicates the presence of methyl and methylene groups, primarily contributed by zein, a hydrophobic protein rich in non-polar side chains. This prominent C-H absorption confirms the incorporation of hydrophobic domains, which is likely to enhance the water resistance and structural cohesion of the nanofiber films. A sharp peak located at approximately 1600 cm^{-1} is assigned to the amide I band, corresponding to the C=O [10] stretching vibration of peptide linkages in the protein backbone, particularly from gelatin [10,39]. This is a key marker of the protein's secondary structure and provides insight into the conformational integrity of the nanofiber films. The presence of this peak also confirms that gelatin retains its structural features after the electrospinning process. The peak near 1500 cm^{-1} is associated with the amide II band, which involves N-H bending and C-N stretching vibrations [40]. This absorption supports the existence of protein-specific structures and suggests potential molecular interactions between gelatin and zein via hydrogen bonding or electrostatic forces. Additional peaks observed in the range of 1242–1247 cm^{-1} are indicative of amide III bands, resulting from N-H bending coupled with C-N stretching [41]. These peaks further confirm the presence of organized secondary structures and possible protein–protein interactions, which may contribute to the mechanical strength and flexibility of the composite films. The peak at 1454 cm^{-1} corresponds to the symmetric deformation of NH_4^+ groups, suggesting the presence of amino acid residues with protonated side chains. This implies that electrostatic interactions could also be involved in stabilizing the composite matrix. Moreover, the absorption band at 1406 cm^{-1} is attributed to C-N stretching vibrations, indicative of the nitrogen-containing functional groups that are integral to protein structures. A smaller peak at 1364 cm^{-1} corresponds to the deformation vibration of methyl groups ($-CH_3$), confirming the contribution of hydrophobic amino acid residues, predominantly from zein. This feature further supports the dual nature of the composite-comprising both hydrophilic (gelatin) and hydrophobic (zein) components-which can be advantageous for tailoring moisture barrier properties in food packaging applications. The relatively lower intensity observed in the broad region between 2930–3300 cm^{-1} may be attributed to the formation of intermolecular hydrogen bonds between hydroxyl groups (from gelatin) and amino groups (from zein). Due to the presence of hydrogen bonds, they enable the formation of a dense network between molecular chains. This network reduces free volume, making the film's micropores tighter and lowering the permeation rates of water vapor and oxygen, thereby delaying fruit dehydration and oxidation. Secondly, hydrogen bonds allow interactions between hydrophilic groups, making them less likely to bind with external water molecules.

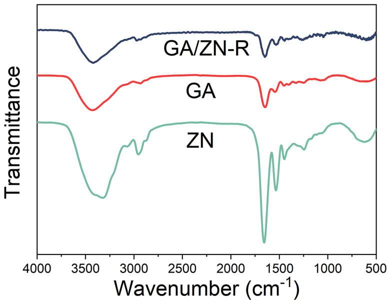

Figure 2: FT-IR images of GA, ZN and GA/ZN-R film.

These interactions reduce the number of free functional groups available for infrared absorption, suggesting successful integration and interaction between the two proteins. Collectively, the FT-IR analysis reveals substantial intermolecular interactions within the composite nanofiber films, particularly hydrogen bonding and potential electrostatic interactions between gelatin and zein. These interactions likely contribute to the enhanced structural stability, mechanical performance, and functional integrity of the composite films. The successful blending of gelatin and zein is further validated by the retention of characteristic protein peaks and the emergence of interaction-specific shifts, supporting the potential application of these nanofiber films in food packaging systems where both strength and barrier properties are critical [42]. In addition to spectroscopic analyses, the surface morphologies and microstructures of the electrospun nanofiber films were characterized using SEM, as shown in Fig. 3. Fig. 3a1 illustrates the morphology of coaxially electrospun composite nanofiber films, with gelatin and resveratrol forming the core solution and zein serving as the sheath (outer) solution. It is well established that the viscosity of the spinning solution significantly influences fiber morphology and diameter during electrospinning. In this study, the incorporation of the zein solution into the coaxial setup led to a notable decrease in overall solution viscosity. As a result, a substantial reduction in average fiber diameter was observed-from 1.67 μm in pure gelatin fibers to 0.91 μm in the coaxial composite fibers, as shown in Fig. 3a2. This decrease can be attributed to the lower viscosity facilitating the stretching and thinning of the jet under the applied electric field, leading to the formation of finer fibers. These findings underscore the importance of rheological properties in tailoring fiber dimensions and optimizing electrospinning parameters for desired material characteristics. As fiber diameter decreases, the pore size distribution within the film becomes more uniform and smaller. This fine-pore network restricts the rapid diffusion of oxygen and water vapor, thereby reducing the fruit's respiration rate and water loss. This process delays fruit ripening and spoilage to a certain extent. Additionally, smaller fiber diameters often imply more thorough stretching of the solution under an electric field, resulting in higher molecular chain orientation within the fibers. This enhances hydrogen bonding, hydrophobic interactions, and van der Waals forces, thereby improving the film's structural stability and water resistance. Fig. 3b1 presents the morphology of zein nanofiber films fabricated via uniaxial electrospinning. The 30% w/v zein solution produced continuous, bead-free, and smooth fibers, demonstrating uniform morphology across replicates. As shown in Fig. 3b2, the average fiber diameter was approximately 138 nm. This nanoscale uniformity reflects the efficacy of the electrospinning process in processing zein into high-quality nanofiber films. The results also emphasize zein's potential for applications that require fine, homogeneous fibrous structures, such as food packaging, drug delivery systems, and biodegradable films. The morphology of the zein nanofiber films produced by uniaxial electrospinning is shown in Fig. 3c1, where the 30% w/v zein solution showed uniform beadless smooth fibers at varying concentrations, and the diameter of the nanofibers of the zein was about 138 nm as can be seen through Fig. 3c2. The morphology of gelatin nanofiber films prepared through uniaxial electrospinning is depicted in Fig. 3d1. Gelatin, as a natural polymer with a high molecular weight and significant hydrogen bonding capacity, tends to form a cross-linked network during electrospinning [43]. This behavior results in the net-like arrangement observed in the SEM images. Furthermore, the SEM micrographs reveal a granular surface morphology, which can be attributed to the stretching, deformation, and partial collapse of gelatin fibers due to its gel-like state during electrospinning. The relatively dark appearance and low transparency in the images are a consequence of the dense molecular structure of gelatin, which impedes light transmission. The higher viscosity of the 16% w/v gelatin solution, in conjunction with the large size and complex structure of gelatin molecules, likely contributes to increased cross-linking and partial aggregation during fiber formation. These factors result in a relatively larger average fiber diameter, measured at approximately 1.67 μm as shown in Fig. 3d2. This observation is consistent with the known relationship between polymer concentration, viscosity, and fiber diameter in electrospinning systems. Overall, the SEM analyses confirm the successful fabrication of nanofiber films with distinct morphological features depending on the spinning technique and solution composition. The results highlight the critical role of solution viscosity and molecular interactions in determining fiber diameter and surface characteristics—key parameters for tailoring nanofiber films performance in targeted applications such as food packaging, biomedical scaffolds, and controlled release systems.

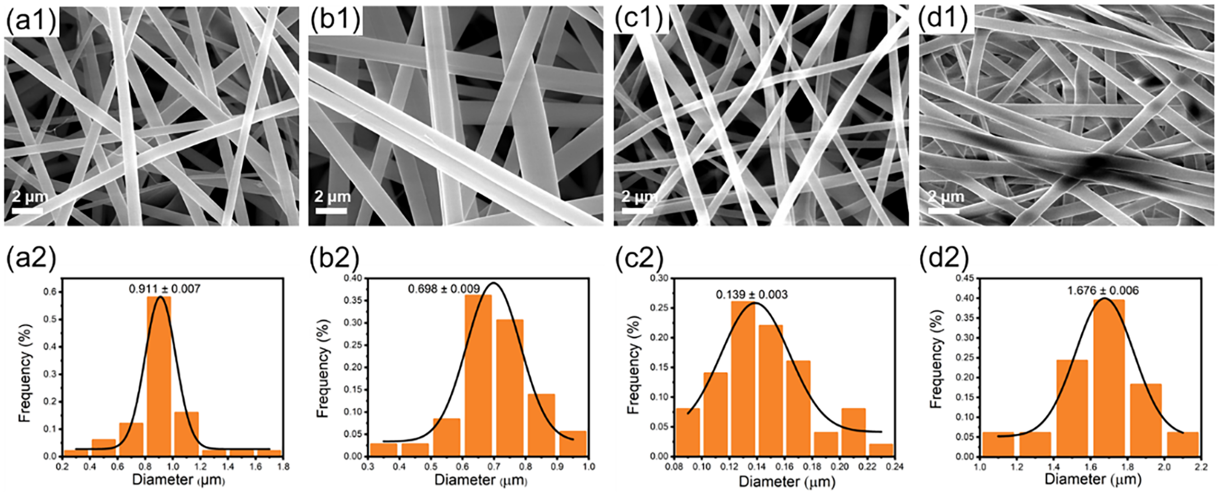

Figure 3: Coaxial electrospinning of GA/ZN-R SEM image (**a1**) at 6000× magnification; (**b1**) at 10,000× magnification; Diameter distribution of GA/ZN-R magnified (**a2**) 6000 times; (**b2**) 10,000 times; (**c1**) Uniaxial electrospinning of ZN SEM image; (**c2**) Diameter distribution of ZN; (**d1**) Uniaxial electrospinning of GA SEM image; (**d2**) Diameter distribution of GA.

3.2 Characterization of Hydrophilicity Properties

WCA measurement is a widely accepted method for assessing surface wettability and hydrophobicity, parameters that are closely influenced by both the chemical composition and microstructure of nanofiber films [44]. In this study, WCA analyses were performed on gelatin-based nanofiber films with and without additives to evaluate how different formulations affect surface hydrophilicity or hydrophobicity. The results are presented in Fig. 4. As depicted in Fig. 4a, the composite film containing resveratrol exhibited a WCA of 105.2°, the highest among all tested samples. This increase can be attributed to the synergistic effect of resveratrol and zein, both of which contribute hydrophobic domains to the nanofiber films surface. The presence of resveratrol may have also influenced fiber morphology by altering intermolecular interactions and promoting a more compact, uniform fiber network, which in turn enhances water resistance [45]. As shown in Fig. 4b, the gelatin nanofiber film exhibited a WCA of 53.0°, indicating its intrinsically hydrophilic nature. This pronounced hydrophilicity is primarily attributed to gelatin's polar functional groups, such as hydroxyl and amino groups, which readily interact with water molecules [46]. Additionally, the high porosity and specific surface area of electrospun gelatin nanofiber films enhance capillary action, promoting rapid water absorption and spreading [11]. These properties make gelatin nanofiber films highly suitable for applications where moisture uptake is beneficial, such as in wound dressings, tissue scaffolds, and biodegradable food packaging systems. In contrast, zein-based nanofiber films, electrospun from a 30% w/v zein solution, demonstrated a significantly higher WCA of 100.6°, as illustrated in Fig. 4c. This elevated contact angle reflects the hydrophobic nature of zein, a prolamin-rich protein composed predominantly of non-polar amino acid residues such as leucine, proline, and alanine [47]. The change in the material's hydrophilicity is consistent with previous related studies [48]. These results indicate that the excellent hydrophobic structure of nanofiber films endows them with superior freshness-preserving properties. The relatively smooth and compact surface morphology of zein fibers, observed in prior SEM analyses, further contributes to water repellency by minimizing surface energy and reducing available surface sites for water interaction. These findings underscore zein's potential in applications demanding moisture barrier functionality, such as water-resistant coatings and packaging materials. Interestingly, the incorporation of resveratrol-a naturally occurring hydrophobic polyphenol-into the GA/ZN coaxial nanofiber films system further enhanced surface hydrophobicity. This result highlights the capacity of hydrophobic additives to modulate the surface properties of biopolymer-based films, providing a strategy for tuning material wettability for specific environmental or functional requirements. Moreover, the observed variations in WCA values also reflect the influence of surface roughness and solution chemistry. The zein-based nanofiber films, spun using an acetic acid solvent, exhibited a smoother and denser surface structure, which is associated with higher contact angles. In contrast, gelatin nanofiber films spun from trifluoroethanol solution tended to display a more irregular and porous surface morphology, promoting hydrophilic behavior. This contrast emphasizes that surface topography-along with inherent chemical composition-plays a critical role in determining water contact behavior. According to the Wenzel and Cassie-Baxter models [49], surface roughness can either amplify hydrophilic or hydrophobic tendencies depending on the nature of the underlying material, an effect clearly demonstrated in the current findings. In conclusion, WCA measurements confirm the strong dependence of nanofiber films surface hydrophobicity on both molecular composition and morphological features. The incorporation of hydrophobic agents such as zein and resveratrol into gelatin-based systems enables the tuning of surface wettability, enhancing their suitability for diverse applications, especially where water resistance is a key performance criterion [11].

Figure 4: WCA figure (**a**) GA/ZN-R, (**b**) GA, (**c**) ZN.

3.3 Freshness Preservation Experiments

The fabricated films exhibited promising potential for antioxidant and antimicrobial applications, which will be further investigated in future studies. To further validate their practical functionality, a real-time preservation study was conducted using strawberries and bananas as representative perishable fruits. These fruits were selected due to their high respiration rates and susceptibility to microbial spoilage, which result in rapid degradation during postharvest storage. Strawberries, in particular, are known for their limited shelf life, with deterioration primarily driven by moisture loss and microbial colonization during ripening. To evaluate the shelf-life extension capabilities of the nanofiber films, strawberries were stored at ambient conditions under three distinct packaging treatments: (1) unwrapped—Blank Control (BC), (2) Commercial Plastic Film- Polypropylene (PP) Plastic Film (PF), and (3) the developed composite nanofiber films (GA/ZN-R). The degradation progression was monitored visually over a 6–8 days period, and representative images are presented in Fig. 5a. By the third day of storage, strawberries in both the blank control and plastic film groups exhibited noticeable signs of microbial spoilage. This included visible mycelial growth, surface discoloration, and structural collapse due to tissue softening. In contrast, strawberries wrapped in the composite nanofiber films maintained their bright red color, structural integrity, and firmness, with no observable signs of microbial contamination or deterioration. The enhanced preservation performance observed in the nanofiber film group is likely attributed to the synergistic effects of its antimicrobial and antioxidant functionalities [10]. The film effectively inhibited microbial growth on the fruit surface and may have also limited oxidative degradation, thereby delaying senescence. The porous yet protective nanofiber films matrix likely contributed to a favorable microenvironment by allowing gas exchange while simultaneously acting as a physical barrier to external microbial infiltration. Notably, strawberries packaged in the composite nanofiber films remained visually and texturally fresh for up to five days, significantly outperforming both the blank and plastic film groups. This extended shelf life highlights the film's potential as a sustainable alternative to conventional packaging materials, particularly in reducing food waste and enhancing postharvest quality. These findings collectively demonstrate the efficacy of the developed nanofiber films in preserving the freshness of perishable fruits, reinforcing their application potential in active and intelligent food packaging systems aimed at extending product shelf life and ensuring food safety under practical storage conditions.

Bananas are climacteric fruits, characterized by a pronounced increase in ethylene production following harvest, which significantly accelerates the ripening and senescence processes. This physiological feature renders bananas an ideal model for assessing the effectiveness of preservation technologies, as the progression of ripening and decay can be directly observed through distinct and measurable changes in physical and sensory attributes [50]. These include a visible transition in peel coloration from green to yellow, a progressive softening of the pulp, and a shift in flavor profile from astringent to sweet-all of which provide clear indicators for monitoring preservation outcomes. Given these characteristics, bananas were incorporated as an additional experimental subject in this study to further evaluate the functional performance of the developed coaxial electrospun nanofiber films. Specifically, a gelatin-based nanofiber films loaded with resveratrol and zein was tested for its capacity to delay ripening and minimize spoilage under ambient storage conditions. As illustrated in Fig. 5b, all three experimental groups-blank control, conventional plastic film, and nanofiber film-exhibited typical ripening behavior from day 0 to day 3, with no significant signs of microbial decay. However, by day 6, both the blank control and plastic film groups began to exhibit visible spoilage, including the formation of darkened spots on the banana peel, a hallmark of overripening and microbial degradation. By day 8, bananas stored in the blank control group were extensively decayed, with nearly the entire surface area covered in rot. Similarly, the plastic film group exhibited substantial degradation, with over 50% of the banana surface showing signs of decay. In stark contrast, bananas packaged with the gelatin-based resveratrol-loaded zein nanofiber films displayed a markedly slower deterioration rate. Only approximately one-third of the peel area exhibited darkened spots, and the overall fruit integrity remained largely intact.

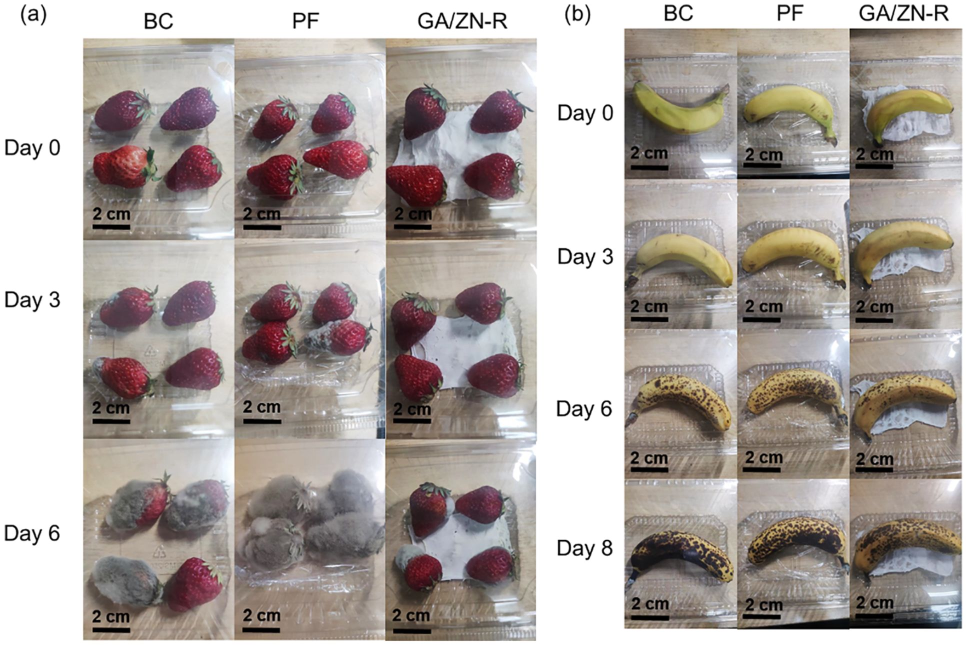

Figure 5: (**a**) Photos of the spoilage process of strawberries in different experimental groups at room temperature three cases; (**b**) Photos of the spoilage process of bananas in different experimental groups at room temperature three cases.

These findings suggest that the composite nanofiber film can provide partial surface protection and a bioactive packaging microenvironment for the stored fruits, rather than requiring complete direct contact with the entire fruit surface. The observed preservation effect is therefore likely associated with the combined roles of the film as a physical barrier and as a carrier of antioxidant and antimicrobial components, which together help retard spoilage and senescence [33,51,52]. In addition, the porous fibrous structure may contribute to moderated gas exchange around the packaged fruit, further supporting postharvest quality maintenance.

To further validate the efficacy of the developed nanofiber films packaging materials, complementary physicochemical assessments were conducted, including weight loss analysis and soluble solid content (°Brix) measurements in fruit samples. These additional evaluations aimed to provide a more comprehensive understanding of the preservation performance of the packaging systems under ambient storage conditions. In the case of strawberries, weight loss was monitored over a day 6 period to quantify the degree of moisture evaporation, which is a critical determinant of fruit freshness and postharvest quality. As illustrated in Fig. 6a,b, the weight loss behavior of bananas stored under different packaging conditions was monitored over a day 9 period to assess the moisture retention capabilities of the developed coaxial electrospun nanofiber films. The results reveal that bananas in the blank control group experienced the most pronounced moisture loss, underscoring the absence of a protective barrier against dehydration. Specifically, on day 3, the weight loss recorded for the blank control, plastic film, and coaxial electrospun nanofiber film groups were 7.8%, 5.5%, and 5.9%, respectively. By day 6, these values increased to 15.5%, 12.6%, and 15.0%, respectively. On day 9, the weight loss reached 24.2% in the blank control group, 18.6% in the plastic film group, and 22.4% in the coaxial electrospun film group under ambient storage conditions (25°C). These findings indicate that while all packaging systems provided varying degrees of moisture retention, the blank control group consistently exhibited the highest water loss, which is closely linked to accelerated senescence and textural degradation in bananas. In contrast, the plastic film and coaxial electrospun nanofiber film groups significantly reduced moisture evaporation, thereby slowing the ripening process and extending fruit freshness. Among the tested systems, the plastic film demonstrated slightly better performance than the nanofiber film in minimizing banana weight loss, particularly in the later stages of storage. This observation may be attributed to the specific physiological characteristics of bananas as climacteric fruits, which produce elevated levels of ethylene and undergo rapid metabolic changes post-harvest. The relatively higher weight loss observed in the nanofiber film group compared to strawberries could be due to the porous nature of the nanofiber films matrix, which, while beneficial for gas exchange and microbial inhibition, may result in slightly increased water vapor transmission under high respiration conditions typical of bananas. Nevertheless, the coaxial electrospun nanofiber films still demonstrated excellent performance in mitigating weight loss compared to the unprotected control and approached the effectiveness of conventional plastic film. This highlights their potential as an environmentally friendly alternative for fruit preservation. The capacity of these biodegradable nanofiber films to provide functional preservation performance makes them a promising candidate for sustainable packaging technologies aimed at extending the postharvest life of climacteric fruits such as bananas. As depicted in Fig. 6c,d, the blank control group exhibited the most significant moisture loss throughout the study, reflecting its exposure to ambient conditions without any protective barrier. On day 2, the recorded weight loss for the blank control, plastic film, and coaxial electrospun nanofiber film groups were 4.5%, 1.5%, and 1.7%, respectively. This trend persisted over the subsequent days, with the weight loss values increasing to 13.7%, 6.8%, and 7.3% by day 4, and further to 24.2%, 13.7%, and 15.0% by day 6, under storage at 25°C. These results clearly demonstrate that strawberries in the blank control group experienced the most rapid moisture depletion, leading to accelerated degradation and reduced shelf life. In contrast, both the plastic film and the coaxial electrospun nanofiber film groups significantly mitigated water loss, preserving the fruits' integrity for a longer duration. Notably, although the plastic film offered a degree of moisture retention, the coaxial electrospun film exhibited superior performance, consistently showing the lowest weight loss across all time points. The enhanced moisture barrier properties of the coaxial electrospun nanofiber film can be attributed to its unique structural characteristics. The tight, porous fiber network not only creates a physical barrier that impedes water vapor transmission but also facilitates moderate gas exchange, thereby preventing condensation while preserving internal humidity levels around the fruit surface. Furthermore, the incorporation of hydrophobic components, such as zein and resveratrol, contributes to reduced water permeability, enhancing the film's ability to retain moisture.

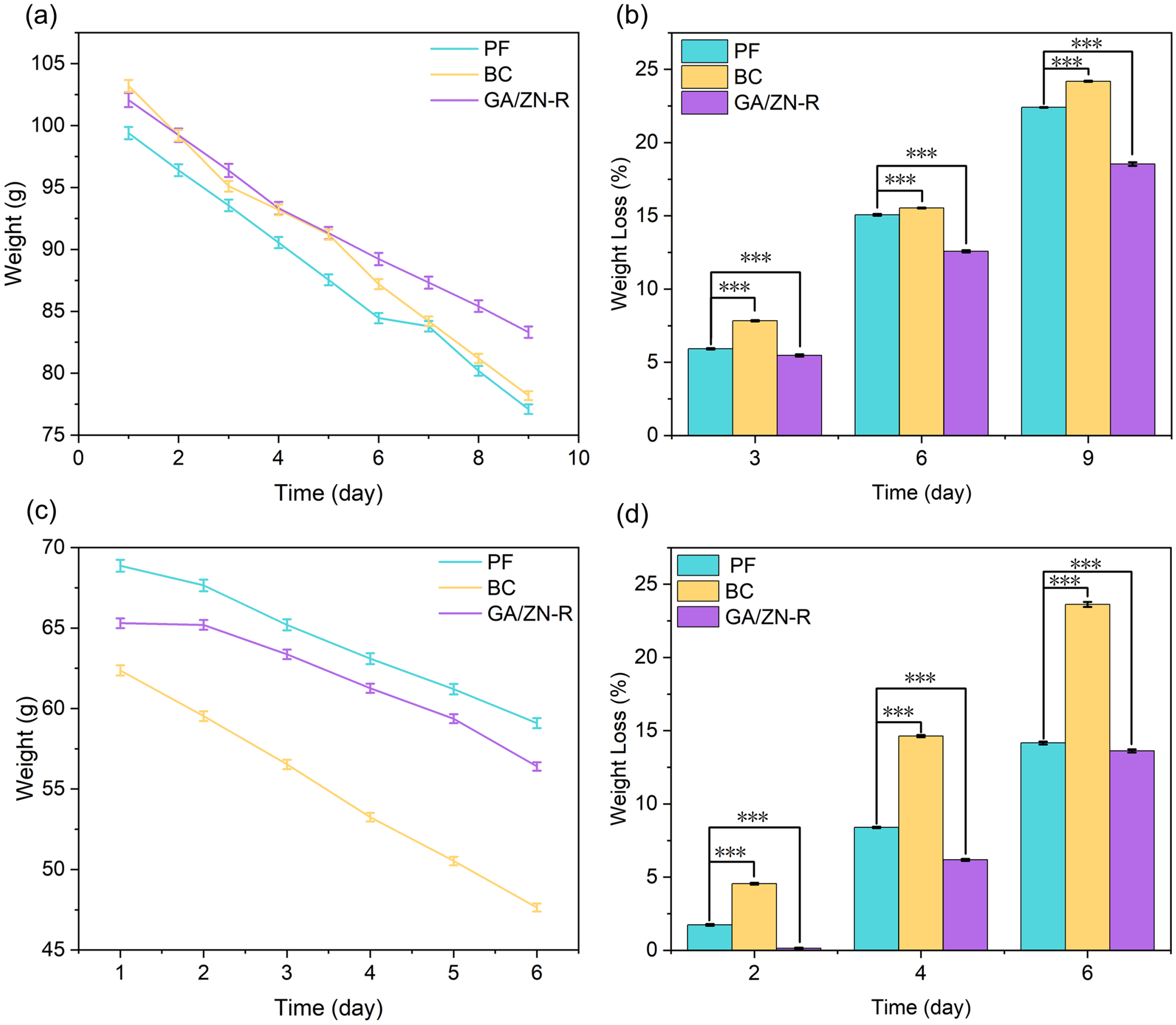

Figure 6: (**a**) The weight changes of fruits stored at 25°C for 6 days under different material coverage conditions, $p < 0.001$; (**b**) Weight loss of bananas stored at 25°C for 6 days, $p < 0.001$; (**c**) The weight changes of strawberries stored at 25°C for 6 days under different material covering conditions, $p < 0.001$; (**d**) Weight loss of strawberries stored at 25°C for 6 days, $p < 0.001$.

These findings emphasize the critical role of packaging material in influencing the water retention capacity of fresh produce. The coaxial electrospun nanofiber film reduced fruit weight loss and helped delay visible postharvest deterioration, thereby demonstrating its potential as a biodegradable alternative to conventional plastic films for active food-packaging applications.

The °Brix test, which measures Total Soluble Solids (TSS), serves as an important indirect indicator of fruit freshness, quality, and ripening status. It reflects the concentration of soluble sugars, organic acids, and other soluble nutrients, thus providing valuable data to support theoretical evaluations of fruit preservation performance [53]. As shown in Fig. 7a, strawberries stored at 25°C under different packaging conditions displayed significant variations in TSS content over a day 6 period. Notably, the strawberries wrapped in gelatin-based composite nanofiber films exhibited significantly higher TSS values compared to those in the blank control and plastic film groups. This result indicates that the composite nanofiber film was more effective in retaining the fruit's soluble solids and minimizing nutrient degradation throughout storage. The elevated TSS values in this group suggest reduced respiration and enzymatic degradation, as well as better moisture retention, likely due to the synergistic barrier and bioactive functions of the nanofiber films. Conversely, strawberries in the blank control and plastic film groups showed comparable TSS values, with no significant differences throughout the storage period. This finding implies that traditional plastic films, despite providing a physical barrier, offer limited capacity to retain soluble solids or inhibit nutrient loss. These packaging systems may permit higher transpiration and oxidative stress, contributing to the deterioration of internal quality. In contrast, the gelatin-based nanofiber films preserved the structural integrity and biochemical composition of the fruit more effectively, highlighting its superiority in maintaining freshness, delaying senescence, and preserving sensory quality.

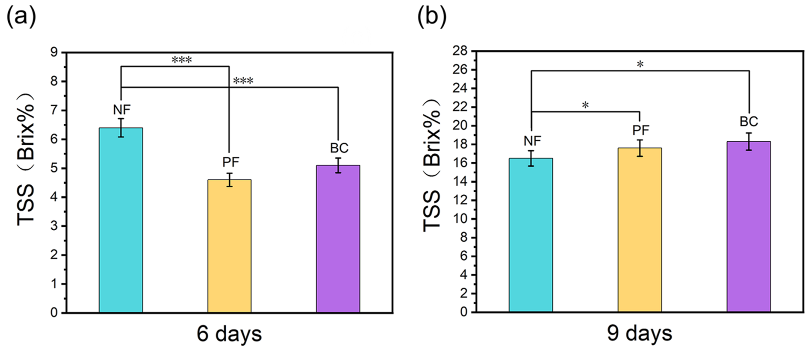

Figure 7: TSS content (in °Brix) stored at 25°C (**a**) strawberries for 6 days; $p < 0.001$; (**b**) bananas for 9 days; $p < 0.05$.

In this case, bananas from the blank control group recorded the highest TSS levels across the day 9 storage period shown in Fig. 7b. This trend reflects an accelerated ripening process, as elevated respiration rates in the absence of packaging led to rapid starch hydrolysis and conversion into soluble sugars such as sucrose, glucose, and fructose. The increase in TSS is indicative of advanced metabolic activity and rapid senescence, both of which compromise shelf life. In contrast, both the plastic film and coaxial electrospun nanofiber film groups showed moderate TSS values with no significant differences between them, suggesting that both packaging strategies moderately inhibited starch breakdown and helped delay the ripening process. However, the most pronounced effect was observed in the group packaged with the composite nanofiber film composed of gelatin and resveratrol as the core and zein as the sheath layer. This group consistently exhibited the lowest TSS values throughout the experiment, indicating a marked suppression of enzymatic hydrolysis and sugar release. These findings highlight the remarkable ability of the composite nanofiber film to retard the ripening process in climacteric fruits such as bananas. The bioactive properties of resveratrol, combined with the physical barrier function of the nanofibrous matrix, likely contributed to the inhibition of ethylene-induced metabolic pathways. Thus, this system not only maintained the external appearance of the fruit but also effectively preserved its internal biochemical composition. Taken together, the TSS analyses in both strawberries and bananas reinforce the efficacy of the GA/ZN-R composite nanofiber film in maintaining fruit quality. By minimizing nutrient degradation and delaying physiological ripening, this novel biodegradable packaging material demonstrates substantial potential for application in postharvest preservation and commercial fresh produce packaging.

To verify the antioxidant performance of the samples, we compared the antioxidant performance of the nanofiber films loaded with resveratrol and those without resveratrol with commercial food packaging films. The experimental results are shown in Fig. 8a. DPPH and ABTS are methods for evaluating antioxidant activity. The experiment found that the commercial food packaging film had very limited free radical scavenging efficiency for DPPH and ABTS. However, when the un-loaded resveratrol nanofiber films were placed in the solution, the purple color of the DPPH solution slightly faded to purplish red, and the blue color of the ABTS solution slightly became lighter under the naked eye. While the resveratrol-loaded nanofiber films placed in the solution showed a significant fading effect within a short period of time. This demonstrated its excellent antioxidant performance, with a scavenging rate of 94.90 ± 0.11% for ABTS and 95.85 ± 0.11% for DPPH. Thus, it can be concluded that loading resveratrol significantly enhanced the antioxidant performance of the nanofiber films, which is helpful for demonstrating excellent preservation performance in food preservation.

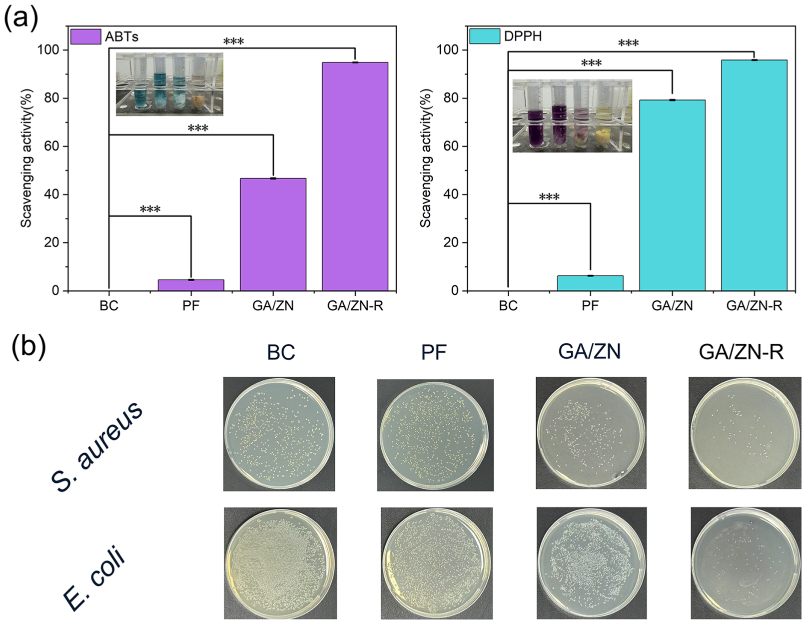

Figure 8: Antioxidant and antibacterial tests. (**a**) DPPH and ABTS scavenging activity of the different samples, $p < 0.001$; (**b**) Bacterial agar plate spreading results.

To evaluate the antibacterial properties of the samples, typical Gram-positive *S. aureus* and Gram-negative *E. coli* were selected as model microorganisms. Using the spread plate method, 4 mg of each sample was incubated with bacterial suspensions for 8 h, followed by incubation at 37°C for 12 h. Colony counts on agar plates were recorded, and the antibacterial rates were calculated. As shown in Fig. 8b, the commercial food wrap exhibited negligible antibacterial activity. Although the nanofiber membrane without resveratrol loading demonstrated a certain degree of antibacterial effect, its performance remained unsatisfactory. In contrast, the resveratrol-loaded nanofiber membrane showed visibly clear zones of inhibition on the agar plates, indicating significant antibacterial activity. Quantitative analysis revealed that GA/ZN-R achieved a bactericidal rate of 91 ± 2% against *S. aureus* and 94 ± 1% against *E. coli*.

This experimental result indicates that the composite nanofiber films exhibit excellent antioxidant activity, mainly due to the addition of resveratrol. Previous studies have shown that resveratrol has antibacterial, anti-inflammatory, anti-obesity and antioxidant properties, and has a strong ability to scavenge free radicals [54]. It can slow down the oxidation of fats and the degradation of nutrients such as vitamins and delay the spoilage process of fruits and vegetables. It can inhibit the activity of enzymes related to cell aging and metabolic disorders and help maintain the active state of fruit and vegetable cells. Moreover, resveratrol can stimulate the fruit's innate defense mechanisms, including the accumulation of phenolic compounds, which enhances resistance to pathogens and further supports preservation. Zein, as a by-product of corn, has been widely used in the field of food safety due to its excellent environmental protection characteristics and the advantage of being purely natural and pollution-free [55]. This study takes advantage of the usability of Zein. By using it as food preservation film, it can not only extend the preservation period of food but also ensure its safety in use. To prevent the material from degrading over time during use and generating toxic and harmful substances adhering to the surface of food. By combining the advantages of different raw materials, the final product was obtained, and the experimental results further confirmed the feasibility of the material [56,57]. However, to further evaluate the practical application potential of the present system, future studies should investigate the release kinetics of resveratrol from the core–shell nanofiber structure and assess the long-term durability of the film under different storage conditions, such as temperature and humidity.

In summary, this study pioneered encapsulation of R within GA/ZN via coaxial electrospinning, achieving both structural stability and freshness preservation in the film. Compared to conventional electrospinning [11,58], coaxial electrospinning enables the preparation of core-shell structured nanofibers. This approach achieves the protection and controlled release of active ingredients, enhances film performance, and facilitates multifunctionalization in food packaging. Consequently, it significantly improves freshness retention and expands application potential. Detailed characterization and analysis of the fabricated nanofiber film were conducted through relevant measurements and experiments. Experimental results demonstrate that this nanofiber film is not only edible but also extends the shelf life of certain fruits (such as strawberries and bananas) by 2–3 days. Compared to gelatin fiber films, the contact angle increased to 105.2°, while the fiber diameter decreased to 0.91 μm. This study presents a novel strategy for the development of edible, biodegradable, and bioactive food-packaging materials, showing promising potential for environmental sustainability and future practical application. The proposed GA/ZN-R core–shell nanofiber film may be particularly suitable for the preservation of fresh produce, such as fruits and vegetables. Nevertheless, although the present work demonstrates the feasibility and preservation capability of this system at the laboratory scale, further investigation is still required to support its industrial translation in terms of scalability and cost-effectiveness. Future studies should therefore focus on increasing production throughput, reducing solvent and energy consumption, and optimizing the fabrication process for continuous and large-scale manufacturing. In addition, more systematic evaluations of raw material costs, process efficiency, and solvent recovery will be essential for assessing the practical feasibility of this system in food-packaging applications.

However, due to the limitations of the experimental period and conditions, this study still has some shortcomings. For example, the mechanical stability of the materials has not yet been evaluated. In future studies, we will address these limitations by optimizing the material composition and conducting more systematic performance tests. We believe that with more rigorous experimental design and comprehensive evaluation, the advantages of these materials can be described more objectively, more reliable conclusions can be drawn, and clearer guidance for subsequent research directions can be provided.

4 Conclusions

In this study, a core–shell nanofiber films structure were successfully fabricated via coaxial electrospinning, wherein resveratrol was loaded into a gelatin solution as the inner core and zein served as the outer sheath layer. Overall, the protein-based composition of the GA/ZN-R nanofiber films provides biodegradability, edibility, and food-contact compatibility, supporting their potential application as sustainable active packaging materials for fresh produce preservation. Furthermore, the incorporation of resveratrol-a natural antioxidant compound-substantially improved the film's ability to preserve food freshness by enhancing its antioxidant capacity and delaying oxidative degradation. Comprehensive characterization of the nanofiber films was conducted, including analyses of fiber morphology, WCA, infrared spectra, and freshness preservation performance. The results confirmed the successful fabrication of the composite nanofiber film and validated its applicability in extending the shelf life and maintaining the quality of perishable food products. The experimental results confirmed that the fabricated nanofiber film is edible and effectively extends the shelf life of fruits such as strawberries and bananas by 2–3 days. Furthermore, the material exhibited a greater contact angle (105.2°) and a smaller average fiber diameter (0.91 μm) than the control gelatin film. The DPPH and ABTS radical scavenging rates were 95.85 ± 0.11% and 94.90 ± 0.11%, and antibacterial rates of *S. aureus* and *E. coli* were 91 ± 2% and over 94 ± 1%, respectively. Overall, this study reports the encapsulation of resveratrol within gelatin/zein core–shell nanofibers using coaxial electrospinning and evaluates their potential as biodegradable active food packaging materials. These materials exhibit antioxidant, antibacterial, and freshness-preserving properties, indicating their potential as biodegradable active packaging materials for fresh produce preservation. This strategy expands the application of preservative materials and provides a reference for the design of other functional materials.

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Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GA/ZN	Gelatin/Zein
GA/ZN-R	Gelatin/Zein-Resveratrol
ZN	Zein
GA	Gelatin
R	Resveratrol
BC	Blank Control
PF	Plastic Film
FT-IR	Fourier Transform Infrared Spectrometer
SEM	Scanning Electron Microscope
WCA	Water Contact Angle
TSS	Total Soluble Solid

PP	Polypropylene
DPPH	2,2-Diphenyl-1-Picrylhydrazyl
ABTS	2,2′-Azino-Bis(3-Ethylbenzothiazoline-6-Sulfonic Acid) Diammonium Salt
E. coli	*Escherichia coli*
S. aureus	*Staphylococcus aureus*

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