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Preparation of biodegradable CNTs-ZnO/cellulose membrane with photothermal antibacterial activity for food packaging application

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Abstract:

Biomass-derived cellulose membranes with antibacterial activity are ideal candidates for food packaging applications due to their biodegradable, environmental suitability and eco-friendliness. However, antibacterial packaging materials are plagued by several drawbacks, including elevated production costs, potential migration risks associated with certain antibacterial agents, and latent adverse effects on human health. Herein, this work proposes a facile and mild method to fabricate a biodegradable CNTs-ZnO/cellulose membrane with photothermal antibacterial activity for food packaging applications. Specifically, the CNTs-ZnO nanoparticles were prepared through the uniform dispersion of acid-treated carbon nanotubes and zinc oxide particles under ultrasonic treatment. Then, the CNTs-ZnO/cellulose membrane was fabricated by in-situ deposition of CNTs-ZnO nanoparticles onto the cellulose surface. It is indicated that the resulting CNTs-ZnO nanoparticles are uniformly distributed within the cellulose membrane, endowing the membrane with photothermal properties and antibacterial activities. Under simulated solar irradiation at 1.8 W/cm^2 , the surface temperature of the CNTs-ZnO/cellulose membrane rapidly increases from $22.0 \text{ }^{\circ}\text{C}$ to $67.2 \text{ }^{\circ}\text{C}$ within 2 min. The antibacterial analysis showed that the inhibition rate of the composite membrane against *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) could reach $>65.66\%$ and $>97.85\%$, effectively reducing the risk of bacterial contamination in food. More importantly, the preservation validation experiments show that the CNTs-ZnO/cellulose membrane extends the shelf life of strawberries by 5 days, with a fruit weight loss rate of only 7%. In addition, the obtained CNTs-ZnO/cellulose membrane shows excellent biodegradability and gas permeability, making it suitable for various food packaging applications.

Keywords: CNTs-ZnO nanoparticles; Antibacterial packaging; Photothermal antibacterial;
Cellulose membrane; Food packaging; Photothermal conversion

1. Introduction

Food packaging materials are essential for protecting food, extending its shelf life, reducing waste, and ensuring convenient transportation and storage. Based on specific application requirements, food packaging materials can be classified into plastic, paper, metal, glass, and composite materials, among others (Bai et al. 2025; Khan et al. 2021). Among these, plastic packaging is widely used in daily life and the food industry due to its lightness and stability, good chemical resistance, and ease of processing and molding (Ouyang et al. 2024; Shlush and Davidovich-Pinhas 2022). However, the applications of plastic packaging suffer from distinct drawbacks, such as environmental pollution, poor heat resistance and difficulty in recycling (Teklemedhin et al. 2026). In the past decades, biomass composite materials have garnered widespread attention in the field of food packaging due to their environmental friendliness, safety, and biodegradability (Perera et al. 2023; Li et al. 2024). These biomass packaging materials not only enable the utilization of renewable resources but also exhibit excellent gas barrier properties, which can effectively extend the shelf life of food products, thus emerging as an ideal option for sustainable packaging solutions (Li et al. 2026). Food spoilage triggered by bacterial contamination not only degrades food quality but also poses severe food safety risks. Although conventional biomass packaging materials can reduce direct contact between external microorganisms and food to some extent, they cannot fundamentally suppress the growth and proliferation of bacteria inside the packaging (Antony et al. 2023). Therefore, to reduce food waste and minimize economic losses, it is essential to develop green antibacterial packaging materials that can inhibit or eliminate bacteria inside the packaging.

Antibacterial packaging materials, which effectively inhibit or eliminate the

24 proliferation of microorganisms, have gained widespread attention for their role in
25 extending the shelf life of food products, reducing food waste, and enhancing the overall
26 quality of packaging systems (Kumar et al. 2025; Yana et al. 2024). To actively inhibit or
27 eliminate pathogenic and spoilage microorganisms, one of the most effective strategies for
28 developing antibacterial packaging materials is the incorporation of organic, natural
29 products (Wang et al. 2025) and inorganic antimicrobial agents (Yao et al. 2024) through
30 techniques such as electrospinning, mild Schiff base reaction, physical blending, surface
31 grafting, and coating (Panda et al. 2026). In this regard, a related study employed nisin-
32 loaded electrospun nanofibers as active food packaging, which could effectively inhibit
33 *S.aureus* and *Listeria monocytogenes* for up to 1.5 years after fabrication (Vencato et al.
34 2025). Similarly, Wang et al. prepared Lysine grafted N-halamine Schiff base type hemp
35 cellulose-based antibacterial material, which shows exceptional antibacterial activity, and
36 the inhibition zone is increased to 18.4 mm (Wang et al. 2022). Although both experiments
37 exhibit excellent antibacterial activity, naturally derived antibacterial materials exhibit poor
38 thermal stability, are easily deactivated, and have short-lived antibacterial activity, and
39 synthetic organic antibacterial materials have potential biotoxicity and are strictly regulated
40 in food contact applications (Wu et al. 2018; Jieying et al. 2024). Currently, extensive
41 research efforts have focused on inorganic antibacterial agents for packaging applications
42 due to their high durability, stability, resistance to environmental factors, and ease of
43 processing, including metal nanoparticles, metal oxides, and metal-organic frameworks
44 (Zanchettin et al. 2023). Among these, metal oxides are widely used in food packaging
45 because their small nanoscale size allows them to easily enter bacterial cells and achieve
46 bactericidal effects (Zhang et al. 2024a). Typically, Saral et al. (K et al. 2019) developed a

47 mahua oil-based polyurethane/chitosan film loaded with 5% nano-ZnO, extending carrot
48 shelf life to 9 days. However, inorganic antibacterial materials suffer from limited broad-
49 spectrum antibacterial activity, high environmental risks caused by nanomaterials or metal
50 ions, and the potential to induce microbial resistance with long-term use. Therefore, the
51 advancement of packaging materials with high antibacterial activity and minimal
52 environmental impact is of great significance for innovation and application in food
53 packaging.

54 Photothermal antibacterial technology, which absorbs light energy and converts it into
55 heat to kill bacteria, has been widely applied in water treatment (Liu et al. 2025), air
56 purification (Kong et al. 2025), food packaging (Sha et al. 2025), and medical devices ,
57 among other fields. By utilizing the heat generated through the absorption of sunlight and
58 the triggering of electron transitions or plasmon resonances, a large number of
59 photothermal conversion materials, including carbon-based materials, metal nanomaterials,
60 and semiconductor materials, have been applied in the antibacterial field (Yang et al. 2025;
61 Luo et al. 2025). For instance, Wang et al. (Wang et al. 2021) developed highly efficient
62 near-infrared photothermal antibacterial membrane with incorporated biogenic CuSe
63 nanoparticles, which allows for $>95\%$ suppression in bacterial growth under NIR
64 irradiation for 30 min. However, relying solely on the photothermal materials for
65 antibacterial purposes is insufficient, as photothermal layer achieves efficient sterilization
66 only under illumination with a certain light intensity. In recent years, many efforts have
67 been carried out on the design and preparation of photothermal composites with the
68 purpose of obtaining higher antibacterial activity. In this regard, Qi et al. (Qi et al. 2022)
69 reported that ZnO was coated with near-infrared (NIR)-photoresponsive polydopamine

(PDA), and then coupled with the antimicrobial peptide (AMP), which exhibit excellent antibacterial efficiency of 99.70% and 100.00% against Gram-negative bacteria and Gram-positive bacteria, respectively. Similarly, Xu et al. (Xu et al. 2024) proposed a novel hydrogel wound dressing that was fabricated by embedding Au nanoparticles-decorated halloysite nanotubes (Au@HNTs) into the lignin-based hydrogel matrix containing polyvinyl alcohol and chitosan, which significantly enhanced inhibition rates of *Escherichia coli* (99.00%) and *Staphylococcus aureus* (98.88%). Nevertheless, the photothermal antibacterial process requires an external light source to trigger the photothermal effect of materials. In the absence of illumination, these photothermal materials are unable to exert their antibacterial functions.

Herein, in this work, the CNTs-ZnO/cellulose composite membrane with excellent photothermal antibacterial activity was prepared by in-situ deposition of CNTs-ZnO nanoparticles on the surface of cellulose membranes for food packaging applications. The composite membrane exhibits excellent photothermal performance; under irradiation with a light intensity of 1.8 W/cm² for 2 minutes, the local temperature on the membrane surface rises rapidly from 22.0 °C to 67.2 °C. More importantly, the remarkable antibacterial activity of the composite packaging was demonstrated by the increased diameters of the inhibition zones against *S. aureus* and *E. coli*. Compared with PE, the composite packaging treatment effectively inhibited mold reproduction on the 9th day of strawberry preservation and controlled the fruit weight loss rate at a low level of 7% under light conditions. This work not only develops a biomass-based CNTs-ZnO/cellulose composite membrane with outstanding photothermal antibacterial and strawberry preservation performance, but also provides a promising strategy for designing green, efficient and practical active food

packaging materials.

2. Experimental section

2.1 Chemicals and materials

The rice straw used for cellulose extraction was obtained from a farm near Jiangsu University (Zhenjiang, China). Sodium hydroxide (NaOH), acetic acid (CH₃COOH), sodium chlorite (NaClO₂), zinc oxide (ZnO) nanoparticles (with diameters of 90-100nm) were from Shanghai Macklin Biochemical Technology Co., Ltd. Calcium chloride (CaCl₂), agar, peptone, and yeast extract were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Gram-negative bacteria *Escherichia coli* (*E. coli*, ATCC 25922) and Gram-positive bacteria *Staphylococcus aureus* (*S. aureus*, CMCC(B)26003) were provided by Shanghai Luwei Technology Co., Ltd. (Shanghai, China). Deionized (DI) water was obtained from the laboratory water-purifying system (Zhenjiang, China), employed throughout the experiment. All chemical reagents were of analytical grade and used according to standards without further purification.

2.2 Preparation of carbon nanotube-ZnO nanoparticles

The carbon nanotube-ZnO nanoparticles with prominent photothermal performance were prepared by means of a wetting dispersion method. In a typical procedure, 2 g of CNTs was added to 500 mL of nitric acid and then subjected to a 4 h hydrothermal treatment at 60 °C to improve the dispersibility and surface reactivity. Subsequently, the mixture was rinsed with distilled water until neutral using a vacuum suction device, and dried in an 80 °C oven for 1 h (Ran et al. 2024). After that, the acid-treated multi-walled carbon nanotubes (MWCNTs) were added to distilled water, followed by sonication in an ultrasonic bath for 30 min (Schematic illustration of the surface modification process of

CNTs is displayed in **Fig. 1a**). Then, zinc oxide nanoparticles were added to the above mixture, and the mixture was subjected to another sonication treatment for 2 h to ensure sufficient dispersion of the ZnO nanoparticles and prevent their aggregation. Finally, the mixture was filtered and dried in an oven at 80 °C for 5 h to obtain the CNTs-ZnO composite nanoparticles.

2.3 Preparation of CNTs-ZnO/cellulose membrane

The biomass cellulose was extracted from rice straw according to the previously reported method with some modifications (Zhang et al. 2026). The detailed information of cellulose extraction is described in the **Supporting Information**.

The CNTs-ZnO/cellulose membrane with excellent photothermal antibacterial performance was prepared by physical crosslinking of cellulose and CNTs-ZnO nanoparticles. Typically, the nanofiller was prepared by dispersing 0.2 g of CNTs-ZnO composite nanoparticles in deionized water under ultrasonic treatment, and the upper layer of the well-dispersed CNT-ZnO suspension was obtained by centrifugation at 5000 rpm. Subsequently, the CNTs-ZnO/cellulose membrane was obtained by vacuum filtration of a mixed solution of CNTs-ZnO suspension and cellulose. The preparation process of CNT-ZnO/cellulose membrane is represented in **Fig. 1b**.

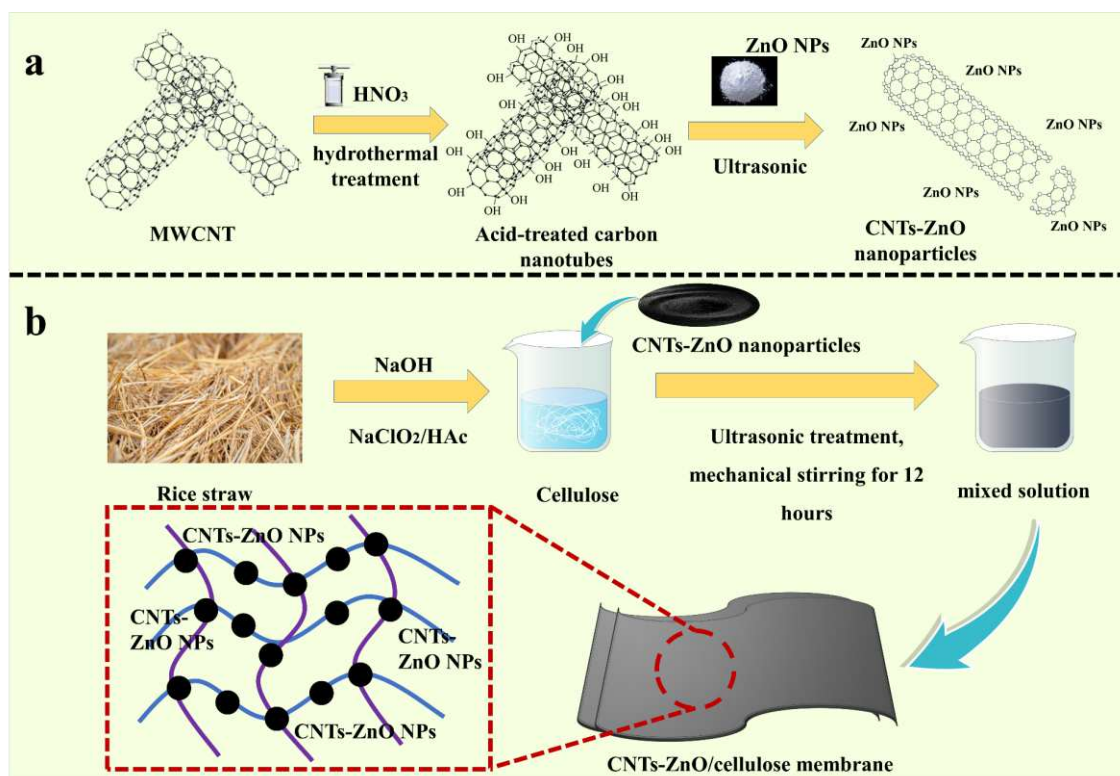


Fig. 1 (a) Schematic illustration of the fabrication process of CNTs-ZnO nanoparticles and (b) CNTs-ZnO/cellulose membrane.

2.4 Characterizations

The microscopic morphologies and elemental analysis of CNTs-ZnO/cellulose membrane were analyzed by field emission scanning electron microscopy (SEM, S-4800, Hitachi, Japan) integrated with an energy-dispersive X-ray spectroscope (EDS). The X-ray diffraction (XRD, 6100Lab, Shimadzu Corporation, Japan) pattern was used to identify the structure of samples with a scanning rate of 4 degrees/min in the 2 Theta range from 10° to 80° via $\text{Cu K}\alpha$ radiation at 40 kV. The IR reflectance and transmittance of the samples were measured by using ultraviolet-visible spectroscopy in the range of 200-800 nm (UV-3600, Shimadzu, Japan) and FT-IR spectrometer (Nicolet IS50, Thermo Fisher Scientific, USA) in the range of $4000\text{--}400\text{ cm}^{-1}$. To evaluate the biodegradability of the composite

membrane, a three-month soil burial test was carried out, and a PE membrane was also buried under the same conditions for comparison.

2.5 Water vapor permeability

The degradation rate of the composite membrane (W_0) in natural soil conditions was analyzed with a soil moisture content of about 5 % (Zhang et al. 2024b). At fixed time intervals (0, 1, 5, 10, 15, 20 days), the composite membrane was washed, dried and measured as W_t . The degradation rate in soil natural conditions was calculated by Eq. (1):

$$\text{Degradation} = \frac{W_0 - W_t}{W_0} \times 100\% \quad (1)$$

According to the reported quasi-cup method, the water vapor transmittance of the composite was measured with some modifications (Zhao et al. 2025). In the experiment, 40 g of calcium chloride was dried in an oven at 120 °C for 48 h to remove its moisture and then transferred to a weighing bottle. The CNTs-ZnO/cellulose membrane and PE membrane were covered on the mouth of the weighing bottle and sealed with an elastic material. All bottles were placed in a desiccator containing saturated sodium chloride (9 °C, RH 82%) and weighed every 6 h for a period of 2 days. Each sample was tested three times in parallel, and the average value was taken as the experimental result. The calculation formula for water vapor transmittance is as Eq. (2):

$$\text{WVP} = \frac{\Delta m \times d}{A \times \Delta t \times \Delta P} \quad (2)$$

where Δm (g) was the change of bottle weigh, d (m) was the thickness of the membrane, Δt (s) was the change of time, A (m²) was the total area of the membrane covering the weighing bottle mouth, the ΔP (Pa) is the difference of partial vapor pressure between the interior of the bottle and the saturated sodium chloride solution at 9 °C.

2.6 Photothermal properties

The photothermal conversion performance of the CNTs-ZnO/cellulose membrane was assessed under simulated solar irradiation from a voltage-tunable CEL-S500/350 xenon light source (China), and real-time temperature of CNTs-ZnO/cellulose membrane was monitored and measured with an NIR thermal imager. Membranes were irradiated using a xenon lamp light source at different power densities (0.5, 1, 1.5 and 1.8 W/cm²), and the temperature profiles were recorded during the two-minute irradiation period. The solar light irradiator was subjected to “on-off” cycles. Under 1.8W/cm² irradiation, the heating-cooling curves of the composite membrane were measured during five laser on-off cycles with natural cooling, so as to evaluate their photothermal stability (Zhu et al. 2025).

2.7 Antibacterial capacity

Antimicrobial properties of the CNTs-ZnO/cellulose membrane were studied by the zone of inhibition method. In a standard procedure, 5 g of peptone, 2.5 g of yeast extract, and 5 g of sodium chloride were added to a conical flask filled with 500 mL of deionized water to obtain the Luria-Bertani (LB) broth. Then, the LB broth was evenly distributed in ten conical flasks with a volume of 250 mL and the conical flasks were sealed with sealing membranes. Subsequently, 5 g of agar was added to LB broth and ultrasonicated for 3 h to prepare solid LB media. In order to reduce bacterial interference, LB broth, LB solid medium, pipette tips, and experimental items were placed in an autoclave and sterilized at 121 °C for 30 min. After 30 min of ultraviolet irradiation on a sterile operating table, the LB solid medium was transferred to Petri dishes, and the LB solid medium was cooled and sealed with a sealing strip. After that, 20–30 µL of *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) were placed in sterilized LB solid mediums and cultured to

logarithmic growth phase at 121 rpm at 37 °C. Then, the LB medium containing bacteria was washed with PBS by centrifugation for 10 min (5000 rpm/min), and the bacterial suspension was diluted to 1.5×10^8 CFU/ mL for later use. Subsequently, ZnO membrane, CNT membrane and CNTs-ZnO/cellulose membrane were cut into 6 mm diameter discs and placed into LB solid medium with 10 μ L of *S. aureus* and *E. coli* (1×10^8 CFU mL⁻¹), respectively. Finally, the LB solid mediums were sealed and transferred to a 37 °C incubator for 24 h. Antibacterial properties of ZnO membrane, CNT membrane and CNTs-ZnO/cellulose membrane were determined by the presence or absence of a zone of inhibition around the respective samples. Meanwhile, to verify the practical antibacterial efficacy of the as-prepared membrane, its inhibitory activity against naturally occurring airborne bacteria was assessed under both dark and light irradiation conditions.

2.8 Application of the strawberry preservation

To examine fresh-keeping application of CNTs-ZnO/cellulose membrane under the light irradiation, strawberries were selected as experimental materials, and three control groups were set up. The specific experimental grouping data are presented in **Table S1**.

Before the testing commenced, strawberries were chosen at the same stage of ripeness to guarantee the accuracy of the experiment. All samples were placed on a clean bench under 9 °C and 70-90% humidity for 9 days, during which the appearance and quality of the strawberries were recorded. The initial mass of the strawberry is recorded as W_0 and the mass is re-recorded after a certain period of storage (W_1). The calculation formula for weight loss rate is as Eq. (3):

$$\text{Weight loss rate (\%)} = (W_0 - W_1) / W_0 \times 100\% \quad (3)$$

3. Results and discussion

3.1 Morphology and structural characterization

The surface morphologies and structures of CNTs-ZnO/cellulose membrane were observed using SEM images, as shown in **Fig. 2a**. The pure cellulose membrane presents a continuous network structure with intricate cross-linking, and fiber overlapping forms a homogeneous defect-free skeleton with uniformly interconnected pores, featuring excellent mass transfer performance (**Fig. S1**). Meanwhile, the rough surface morphology of cellulose and its flexibly modifiable surface chemical properties lay an important foundation for its application in food packaging materials. As shown in **Fig. S2**, the CNT structure was loaded on the cellulose surface, and formed a tight interfacial bonding and a continuous composite network with the cellulose matrix through hydrogen bonding interactions. In addition, uniformly monodispersed carbon nanotubes in the composite membrane expose active sites for broad-spectrum light absorption through their conjugated structure, providing the membrane material with core photothermal conversion units. As illustrated in **Fig. 2a**, the surface morphologies of CNTs-ZnO/cellulose membrane were similar to those of the CNTs/cellulose membrane. This was attributed to the fact that ZnO NPs modified carbon nanotubes did not change their intrinsic structure. **Fig. 2b** shows the SEM-EDS mapping of CNTs-ZnO/cellulose membrane, showing the uniform distribution of C, O, and Zn elements with atomic percent of 76.88%, 17.32% and 5.81%, respectively. **Fig. 2c and 2d** shows the uniform distribution of carbon and zinc on the cellulose surface. The results demonstrated that the CNTs-ZnO nanoparticles were successfully coated on the cellulose surface via an in-situ load method.

FTIR spectra analysis of membranes was performed to assess the interaction between

CNTs-ZnO NPs and the biopolymer matrix (**Fig. 2e**). The peak at 1095 cm^{-1} is a characteristic peak for the C-O group, which indicates the tight cross-linkage of cellulose. After the incorporation of CNTs and CNTs-ZnO NPs, there were no obvious differences in the characteristic peaks compared with the pure cellulose membrane, indicating that CNTs and CNTs-ZnO NPs were not linked by chemical bonds. The absorption bands between $3100\text{-}3600\text{ cm}^{-1}$ gradually tended to flatten upon addition of CNTs or CNTs-ZnO NPs, while there was an obvious redshift of O-H (3300 cm^{-1}) in the CNTs/cellulose membrane or CNTs-ZnO/cellulose membrane. The redshift indicated the formation of hydrogen bonds between CNTs or CNTs-ZnO NPs and the cellulose matrix. Compared with the CNTs/cellulose membrane, a new absorption band at $400\text{-}510\text{ cm}^{-1}$ appeared in the spectrum of the CNTs-ZnO/cellulose membrane. This can be explained by the successful modification of acidified carbon nanotubes with ZnO NPs.

In order to investigate the crystalline phase transformation during materials preparation, the crystal structures of as-synthesized samples were characterized by XRD, and the results are shown in **Fig. 2f**. As shown in **Fig. 2f**, the pure cellulose displayed three cellulose I characteristic peaks at 2θ of 14.98° , 16.67° and 22.74° , corresponding to the typical (110), (110) and (200) planes of cellulose respectively. After the introduction of CNTs, the main diffraction peaks of cellulose remained unchanged, indicating that the addition of CNTs did not destroy the basic crystal structure of cellulose. In addition, the typical peaks of CNTs at $2\theta = 26.5^\circ$ were also detected, indicating the successful integration of CNTs into the cellulose matrix. Compared with the cellulose membrane, the CNTs-ZnO/cellulose membrane retained the crystalline structure of the cellulose, demonstrating that the cellulose I crystalline structure was preserved during the loading of CNTs-ZnO

NPs on the cellulose surface. The weakened diffraction signals of cellulose further confirm the effective immobilization of CNTs-ZnO NPs on cellulose. Furthermore, characteristic diffraction peaks were observed at $2\theta = 31.82^\circ, 34.53^\circ, 36.38^\circ, 47.57^\circ, 56.76^\circ, 62.89^\circ, 68.04^\circ$ and 69.12° , which correspond to the reflections of (100), (002), (101), (102), (110), (103), (112) and (201) respectively. These peaks are assigned to the typical wurtzite (hexagonal) structure of ZnO (JCPDS No. 89-7102) with lattice constants $a = 0.3247$ nm and $c = 0.5202$ nm, revealing high crystallinity of the ZnO NPs. The (002) peak intensity is stronger than those of the (100) and (101) peaks, indicating that the c-axis is the preferential growth direction of ZnO NPs. The XRD results were in good agreement with SEM and FT-IR characterizations, further proving that the CNTs-ZnO/cellulose composite membrane was successfully fabricated.

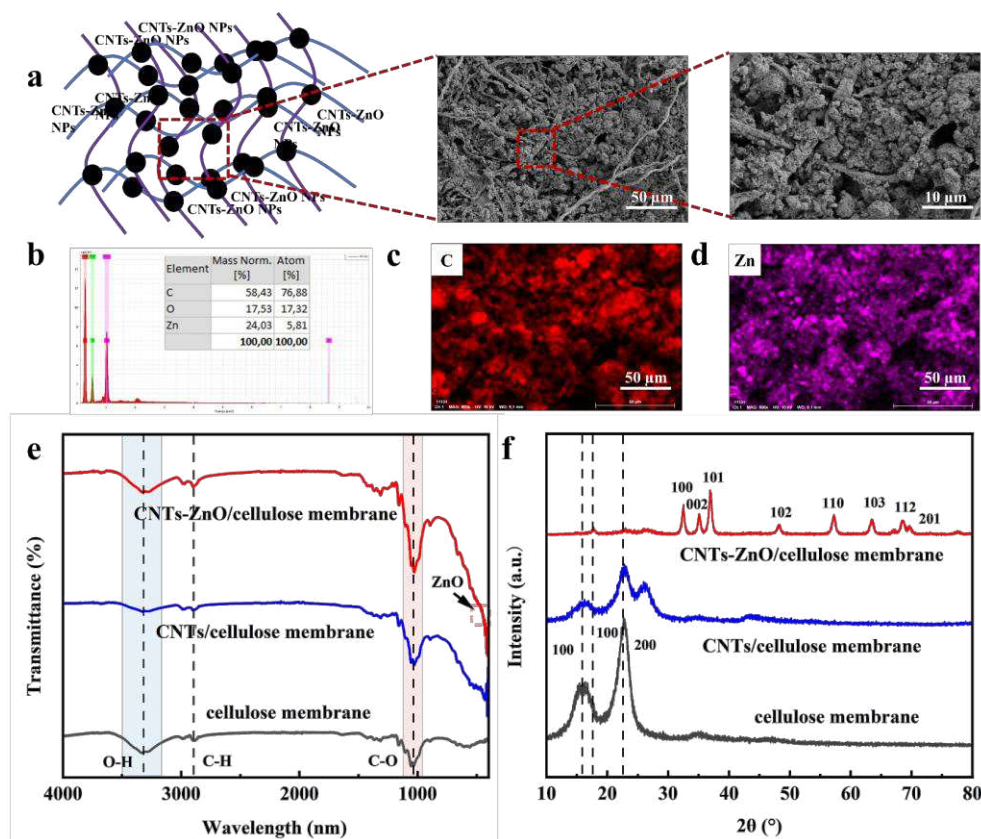


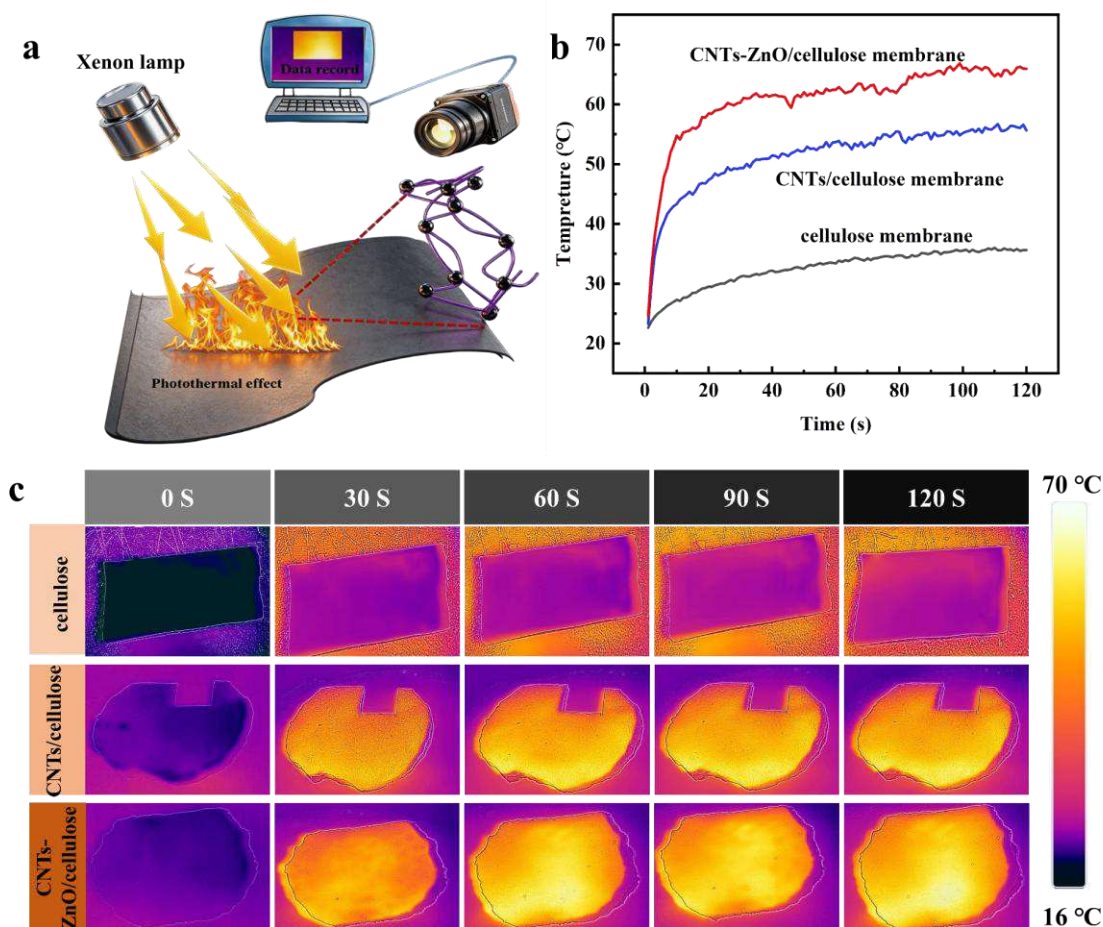
Fig. 2 Structure diagram and SEM images of CNTs-ZnO/cellulose membrane (a). EDX spectrum and elemental distribution data for CNTs-ZnO/cellulose membrane (b). SEM-EDS mapping images of C and Zn elements in the CNTs-ZnO/cellulose membrane (c, d). FT-IR spectra (e) and XRD (f) patterns of cellulose membrane, CNT cellulose membrane and CNTs-ZnO/cellulose membrane.

3.2 Photothermal conservation performance

Photothermal behavior of the CNTs-ZnO/cellulose membrane is a light-to-heat conversion process, and the precisely controlled thermal output can effectively delay the spoilage of perishable foods. The regulation of photothermal conversion efficiency, temperature response behavior and stability of the membrane materials by the incorporation of CNTs-ZnO NPs directly determines the potency and durability of the antibacterial effect. As depicted in **Fig. 3a**, the photothermal properties of membranes were

investigated by simulated solar illumination, and IR thermal imaging was used to record surface temperature variations. **Fig.3b** shows the varying surface temperatures of three membranes, and all of them displayed a positive correlation with the rising exposure time of simulated solar illumination. After the irradiation for approximately 120 s, the cellulose membrane and CNTs/cellulose membrane exhibited saturation temperatures of 25.4 °C and 56.3°C respectively (**Fig.3b**). Under identical irradiation time, the CNTs-ZnO/cellulose membrane attained the maximum saturation temperature of 65.3 °C. The corresponding IR thermal images of the three membranes at different irradiation time points (0 s, 30 s, 60 s, 90 s, 120 s) are shown in **Fig. 3c**. With the extension of irradiation time, the cellulose membrane showed only negligible temperature rise, while the CNTs/cellulose membrane and CNTs-ZnO/cellulose membrane exhibited higher and more uniform surface temperature, which was consistent with the results of the temperature rise curves. The enhanced maximum saturation temperature observed for the CNTs-ZnO/cellulose membrane was primarily driven by CNTs-ZnO nanoparticles, demonstrating that CNTs, as the core photothermal conversion unit, successfully endowed the cellulose-based membrane with excellent photothermal performance, and further introduction of ZnO could generate a synergistic effect with CNTs to further improve the photothermal conversion efficiency of the composite membrane. This result was ascribed to the synergistic photothermal effect of CNTs-ZnO nanoparticles, which promotes the efficient separation and non-radiative relaxation of photogenerated carriers, and improves the full-spectrum light absorption efficiency. The collected incident electromagnetic energy is then converted into thermal energy, and is transferred to the cellulose matrix and surrounding media through phonon transport and lattice vibration of the constructed three-dimensional

305 thermal conductive network, thereby significantly increasing the local temperature of the
 306 membrane and reaching the maximum photothermal local temperature.



307 **Fig. 3** Schematic diagram of the film under sun irradiation (a). Under 1.8 W/cm^2 irradiation,
 308 temperature changes of cellulose membrane, CNTs/cellulose membrane and CNTs-
 309 ZnO/cellulose membrane (b). Temperature changes of cellulose membrane,
 310 CNTs/cellulose membrane and CNTs-ZnO/cellulose membrane (c).

311 The photothermal performance of CNTs-ZnO/cellulose membrane was also
 312 influenced by the varying power density of the simulated solar illumination. As depicted
 313 in **Fig.4a**, the CNTs-ZnO/cellulose membrane rapidly reached saturation temperatures of
 314 $31.88 \text{ }^\circ\text{C}$, $45.86 \text{ }^\circ\text{C}$, $56.29 \text{ }^\circ\text{C}$ and $62.23 \text{ }^\circ\text{C}$ at 0.5 W/cm^2 , 1 W/cm^2 , 1.5 W/cm^2 and 1.8

W/cm², respectively. **Fig.4b** demonstrated the photothermal stability of the CNTs-ZnO/cellulose membrane under simulated solar illumination with a power density of 1.8W/cm². The CNTs-ZnO/cellulose membrane exhibited no significant degradation over five cycles, revealing remarkable photothermal stability and sensitivity. Meanwhile, the optical properties of CNTs-ZnO/cellulose membrane were investigated through UV shielding properties. The UV-Vis transmittance of composite membrane was measured in the wavelength range of 200-800 nm. As shown in **Fig. S3**, the cellulose membrane exhibited satisfactory transparency but poor UV-blocking properties in the near-ultraviolet and visible regions. After the introduction of CNTs and CNTs-ZnO nanoparticles, the transmittance of CNTs/cellulose membrane and CNTs-ZnO/cellulose membrane decreased significantly, both maintaining a transmittance below 10% in the full test spectrum. It is indicated that the as-prepared CNTs-ZnO/cellulose membrane possessed excellent photothermal conversion efficiency, rapid temperature response, good cycling stability and full-spectrum light absorption capacity, which could provide sufficient and stable thermal energy support for the subsequent synergistic photothermal antibacterial application. And the incorporation of nanoparticles greatly enhanced the full-spectrum light capture ability of the composite membrane, which provided a core foundation for efficient photothermal conversion.

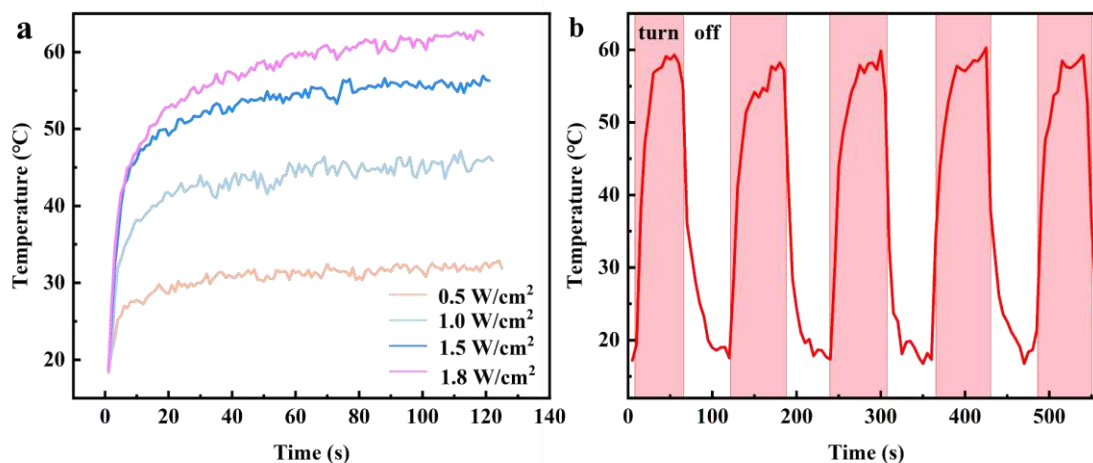


Fig. 4 Temperature changes in CNTs-ZnO/cellulose membrane irradiated using 0.5 W/cm², 1 W/cm², 1.5 W/cm², 1.8 W/cm² (a). CNTs-ZnO/cellulose membrane irradiated for five on/off cycles (b).

3.3 Antibacterial performance

The proliferation of foodborne microorganisms is the primary cause of food spoilage and quality deterioration during storage, particularly for fresh fruits and vegetables, which in turn diminishes their edible and commercial value and increases the risk of foodborne illnesses. The photothermal antibacterial activity of the composite membrane was shown in **Fig. 5a**. As shown, the *E. coli* and *S. aureus* were eliminated under the NIR irradiation. ZnO NPs can generate reactive oxygen species and release Zn²⁺ to induce cell membrane disruption, resulting in bacterial death. Similarly, CNTs-ZnO NPs could also eliminate bacteria, which endow them with not only the function of ZnO NPs but also the ability to convert light into heat via CNTs. Therefore, the CNTs-ZnO/cellulose membrane exerted a superior bacteriostatic effect to than ZnO membrane or CNTs/cellulose membrane. The antimicrobial performance of composite membrane was investigated by inhibition zone method (**Fig. 5**). As shown in **Fig. 5b**, the *E. coli* multiplied rapidly on the medium and

quickly spread throughout the medium without NIR irradiation. While the *E. coli* treated by CNTs-ZnO/cellulose membrane was suppressed and did not multiply under the irradiation of NIR (the inhibition rate was close to 100% as shown in **Fig. 5c**). This was due to the inherent ability of CNTs-ZnO NPs to act as photothermal bactericides for killing the bacteria. The same trend was seen with the growth of *S. aureus* as shown in **Fig. 5d**. Under the irradiation of NIR, the *S. aureus* treated by CNTs-ZnO/cellulose membrane was also suppressed and no bacterial multiplication occurred (the inhibition rate was close to 65.66% as shown in **Fig. 5e**). This difference may be attributed to the thicker peptidoglycan layer in the cell wall of Gram-positive *S. aureus*, which provides greater resistance to heat and reactive oxygen species, whereas the outer membrane of Gram-negative *E. coli* is more susceptible to disruption under photothermal treatment, leading to a higher inhibition rate.

In addition, to further verify the antibacterial potential of the as-prepared CNTs-ZnO/cellulose membrane in practical application scenarios, the antibacterial activity against naturally occurring airborne bacteria was evaluated under dark and light conditions as shown in **Fig. S4**. As illustrated in **Fig. S4**, the pure cellulose membrane (control) had no antibacterial activity against airborne bacteria in vitro before and after near infrared irradiation. Similarly, the CNTs/cellulose membrane (control) exhibit only insignificant antibacterial activity, because airborne bacteria constantly settle on the membrane surface, forming a bio-membrane barrier and block contact with the CNTs. In contrast, the antibacterial activity of the composite membrane gradually increased by in-situ deposition of CNTs-ZnO NPs onto cellulose surface. As shown in **Fig. S4**, the composite membrane exhibited excellent antibacterial ability against airborne bacteria, and the diameter of inhibition zone was 22.12mm (light) and 19.57mm (dark). Therefore, the excellent

photothermal effect of the membrane makes it have excellent antibacterial performance to kill airborne bacteria.

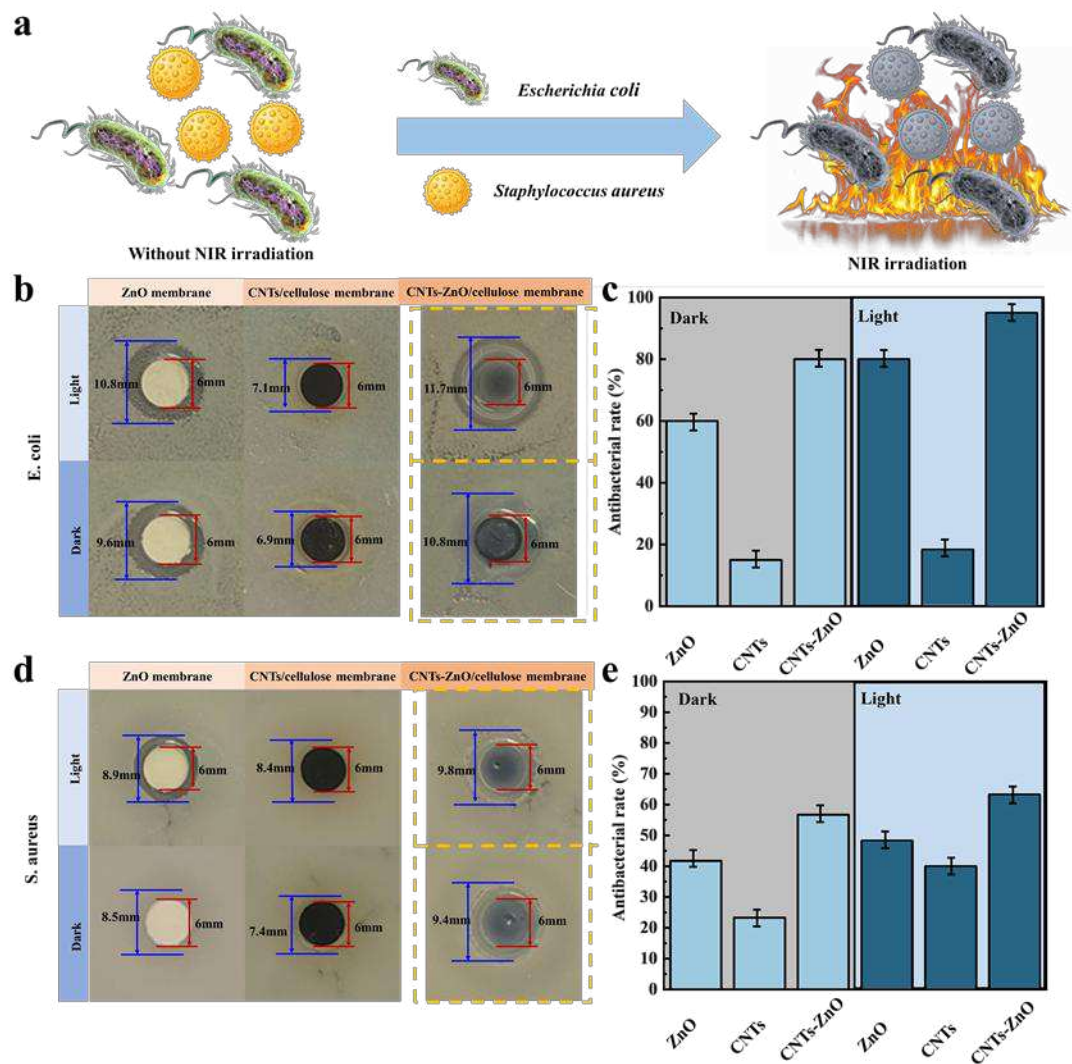


Fig. 5 (a) Antibacterial mechanism of CNTs-ZnO/cellulose membrane. Light-enhanced antibacterial activity of composite membrane against *E. coli* and *S. aureus* evaluated by inhibition zone method. Inhibition zone images against *E. coli* (b) and *S. aureus* (d) under dark and light irradiation. Corresponding antibacterial rate of the fabricated composite membranes (c, e).

3.4 Biodegradability and Water Vapor Permeability

Biodegradability is an important factor for measuring the environmental friendliness of composite membrane and it can solve the disadvantages of traditional oil-based plastic packaging materials. **Fig. 6a** shows the biodegradation process of composite membrane in natural soil from 0 day to 20 days. As shown in **Fig. 6a**, the CNTs-ZnO/cellulose could be degraded at the end of 20 days. Compared to PE membrane, the composite membrane is environmentally friendly due to its degradable properties. With the increase of time, the degradation of composite films also gradually increased under the effect of microorganisms in soil.

The water vapor permeability (WVP) of the composite membrane acts as a core regulatory factor for the internal humidity microenvironment of the package and the balance of enclosed food, which directly dominates the water retention capacity, weight loss rate and sensory quality of food during the entire storage period. A better WVP is beneficial to reduce the transfer of water vapor between the outside world and food, and achieve a better food preservation effect. As shown in **Fig. 6b**, the WVP gradually decreased from $2.542 \times 10^{-10} \text{ g}\cdot\text{m}/\text{m}^2\cdot\text{Pa}\cdot\text{s}$ of cellulose membrane to $6.427 \times 10^{-11} \text{ g}\cdot\text{m}/\text{m}^2\cdot\text{Pa}\cdot\text{s}$ of CNTs-ZnO/cellulose membrane. Thanks to the good dispersion and biological interface adhesion of CNTs-ZnO NPs fill into the gaps of the network structure formed by cellulose. It promoted the closer cross-linking between nanoparticles and the polymer matrix, and further led to the reduction of the adsorption rate of water on the membrane surface and the migration rate inside. Compared with PE membrane, the WVP of composite membrane is higher, which could help avoid excessive humidity saturation and condensation buildup inside the package while still reducing excessive water loss.

Therefore, the composite membrane is more suitable for the preservation of fresh fruits with high respiratory metabolism due to its favorable water vapor permeability.

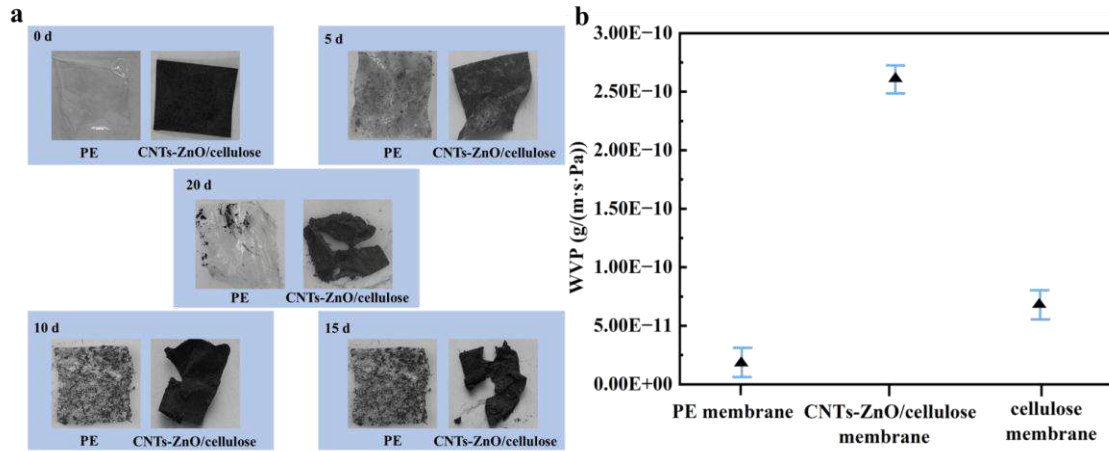


Fig. 6 Degradation images of PE membrane and CNTs-ZnO/cellulose membrane in soil from 0 d to 20 d (a). Weight change curves of PE membrane and CNTs-ZnO/cellulose membrane in water vapor transmission test (b).

3.5 Food preservation application

To demonstrate the application potential of the as-prepared CNTs-ZnO/cellulose membrane in postharvest preservation, fresh strawberry fruits were selected as the model produce and wrapped with the resultant membrane. Untreated air-exposed strawberries and polyethylene (PE)-film-packaged strawberries were set as two control groups. **Fig. 7a** shows the time-dependent mass change of strawberries during storage, **Fig. 7b** summarizes the mass loss rate of strawberries at different storage intervals, and **Fig. 7c** exhibits the visual appearance of strawberries after 9 days of storage. For the air-exposed group, strawberries exhibited obvious surface darkening by Day 3, followed by tissue collapse and microbial decay by Day 7. PE packaging effectively limited the mass loss to 3.0% through a complete moisture barrier (**Fig. 7b**), yet the accumulation of water molecules on

the strawberry surface promoted mold growth, and mold colonies fully covered the entire fruit surface by the 9th day of storage. By contrast, strawberries in the light irradiation group maintained better sensory quality throughout the storage period, with bright red color, plump morphology and fresh calyxes observed within 7 days of storage, and no severe mildew or shrinkage occurred until the end of storage (9 d). In contrast, strawberries wrapped with the composite membrane under dark conditions exhibited earlier surface darkening and calyx wilting, and more pronounced fruit shrinkage on Day 9. This visual quality difference was in good agreement with the weight loss trend (**Fig. 7a, b**), confirming that the photothermal effect of the CNTs-ZnO/cellulose membrane further enhanced its preservation performance on postharvest strawberries. The improved fresh-keeping effect was mainly ascribed to the synergistic effect of the membrane's excellent water vapor permeability and light-enhanced antimicrobial activity, which effectively retarded oxidative deterioration, moisture loss and microbial spoilage of strawberries during storage.

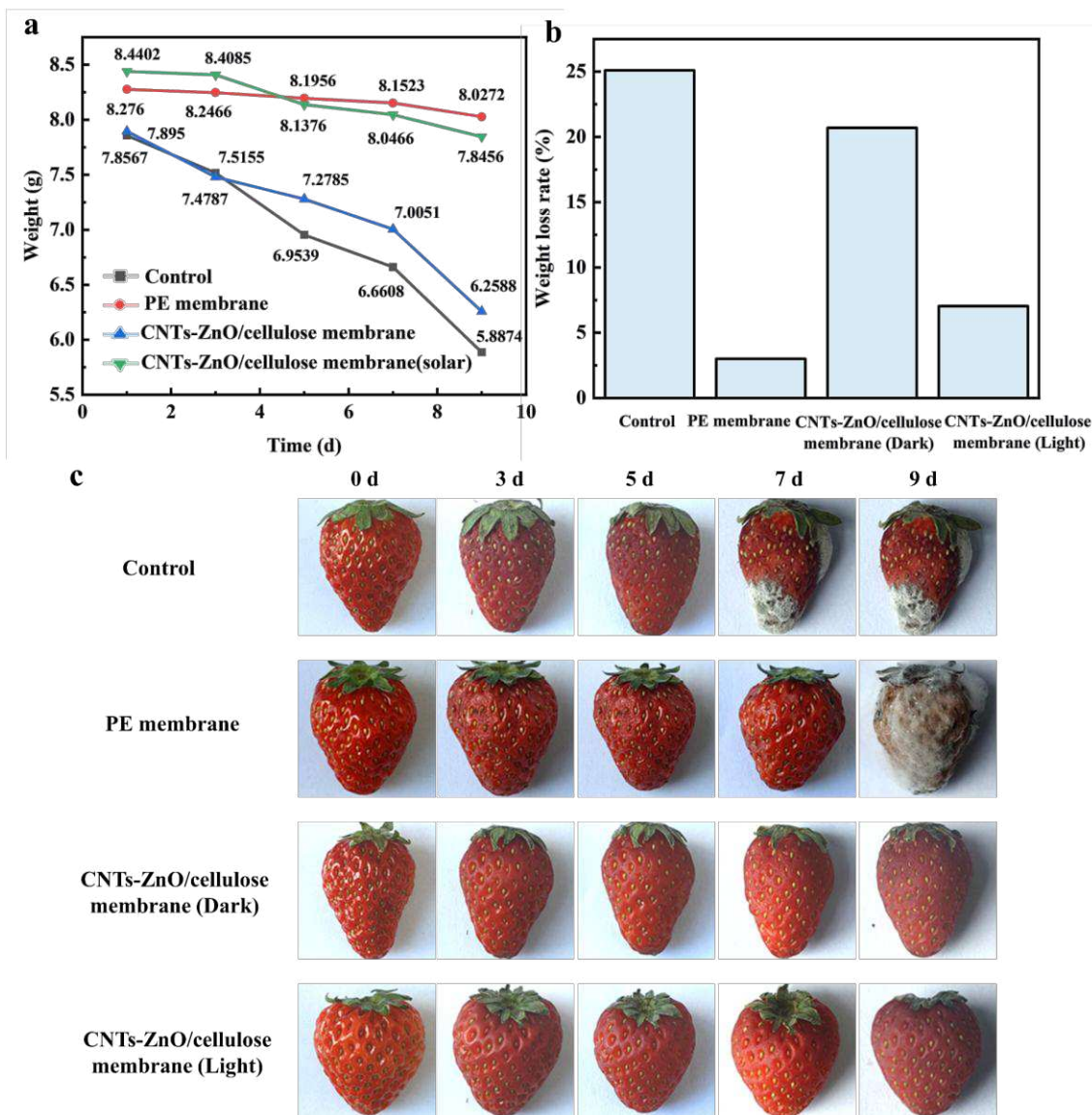


Fig. 7 Dynamic changes in the cumulative weight of strawberries with different packaging treatments during storage (a). Weight loss rate of strawberries in different groups after 9 days of storage (b). Visual appearance changes of strawberries packaged with control, PE membrane, CNTs-ZnO/cellulose membrane (Dark) and CNTs-ZnO/cellulose membrane (Light) at 0, 3, 5, 7 and 9 days of storage (c).

4. Conclusions

This study developed a biodegradable CNTs-ZnO/cellulose membrane with

435 photothermal antibacterial activity for active food packaging applications. Through
436 hydrogen bonding interactions and the in-situ deposition of CNTs-ZnO NPs on the
437 cellulose matrix, the composite membrane formed a dense and compact structure, which is
438 critical for barrier performance enhancement. As a multifunctional nanofiller, CNTs-ZnO
439 NPs not only endowed the membrane with excellent photothermal conversion efficiency
440 and broad-spectrum antibacterial activity but also optimized its water vapor permeability
441 to a moderately low level, which is ideal for high-moisture fresh produce preservation.
442 Consequently, the CNTs-ZnO/cellulose membrane effectively maintained the quality of
443 fresh strawberries, with a fruit weight loss rate of only 7%. This innovative design offers a
444 promising strategy for fabricating active packaging membranes that combine UV shielding,
445 light-induced sterilization, and moisture regulation with renewable cellulose-based
446 materials.

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450 **Author Contributions**

451 Ran Li: Investigation, Formal analysis, Methodology, Writing – original draft.
452 Yuanpan Zhang: Investigation, Formal analysis, Methodology. Hanlin Zhang: Software,
453 Methodology, Visualization. Xuejie Yue: Investigation, Formal analysis. Dongya Yang:
454 Supervision, Project administration, Methodology, Writing – review & editing. Tao Zhang:
455 Investigation, Formal analysis. Fengxian Qiu: Supervision, Project administration,
456 Methodology, Writing – review & editing.

457 **Data Availability:** Data will be made available on request.

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Declarations

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Ethical approval and consent to participate: This paper does not involve any human or animal experiments. Not applicable.

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References

Bai F, Chen G, Liu Y, Liao Z, Jiang Z, Hu Y, Hou R, Li H, Peng C, Wan X, Cai H (2025) Tea storage process: Flavor scalping in green tea caused by plastic packaging materials. Food Packaging and Shelf Life 48: 101451. <https://doi.org/10.1016/j.fpsl.2025.101451>

Khan M R, Ouladsmame M, Alammari A M, Azam M (2021) Bisphenol A leaches from packaging to fruit juice commercially available in markets. Food Packaging and Shelf Life 28: 100678. <https://doi.org/10.1016/j.fpsl.2021.100678>

Ouyang S, Wang F, Liu Y, Ma S, Li M, Wu Y, Hu Z, Zhang S, Wang L (2024) Advances in the enhancement of mechanical and hydrophobic properties of nanocellulose-based packaging materials: A review. International Journal of Biological Macromolecules 282: 137392. <https://doi.org/10.1016/j.ijbiomac.2024.137392>

Shlush E, Davidovich-Pinhas M (2022) Bioplastics for food packaging. Trends in Food Science & Technology 125: 66-80. <https://doi.org/10.1016/j.tifs.2022.04.026>

Teklemedhin T B, Guo Y, Li H (2026) Advancements, challenges, and opportunities of active bio-composite films for food packaging and preservation: A comprehensive review. Food and Bioproducts Processing 156: 537-559.

481 <https://doi.org/10.1016/j.fbp.2026.02.008>

482 Perera K Y, Jaiswal A K, Jaiswal S, (2023) Biopolymer-Based Sustainable Food Packaging
483 Materials: Challenges, Solutions, and Applications. Foods 12(12): 2422.
484 <https://doi.org/10.3390/foods12122422>

485 Li P, Zhou X, Jian B, Zhou M, Liu R, Sun B, Li X, Wang Y, Zhou B (2024) Facile
486 preparation of soybean protein-based oil-resistant paper for food packaging. Industrial
487 Crops and Products 222: 119431. <https://doi.org/10.1016/j.indcrop.2024.119431>

488 Li H, Hua C, Mukhtar A, Abugri A, Yu X, Zhou C, Ma H (2026) Sequential recovery of
489 phenolics, starch, and cellulose from potato peel waste and their valorization into
490 preservative films. Food and Bioproducts Processing 157: 1-13.
491 <https://doi.org/10.1016/j.fbp.2026.02.019>

492 Antony T, Cherian R M, Varghese R T, Kargarzadeh H, Ponnammma D, Chirayil C J, Thomas
493 S (2023) Sustainable green packaging based on nanocellulose composites-present and
494 future. Cellulose 30: 10559-10593. <https://doi.org/10.1007/s10570-023-05537-6>

495 Kumar L, Tyagi P, Lucia L, Pal L (2025) Innovations in Edible Packaging Films, Coatings,
496 and Antimicrobial Agents for Applications in Food Industry. Comprehensive Reviews
497 in Food Science and Food Safety 24: e70217. <https://doi.org/10.1111/1541-4337.70217>

499 Yana L, Yutong C, Qinghui H (2024) Antibacterial films based on polylactide and
500 polybutylene adipate terephthalate loaded with zinc oxide or silver nanoparticles:
501 Characterization and application in fresh noodles packaging. Journal of Food
502 Engineering 367: 111889. <https://doi.org/10.1016/j.jfoodeng.2023.111889>

503 Wang Y, Yu Y, Shi C, Ren Y, Han J, Wu R (2025) Development of curcumin nanoparticle-

504 modified photodynamic gelatin/PVA–chitosan bilayer films for preserving bigeye
 505 tuna. *International Journal of Biological Macromolecules* 308: 142299.
 506 <https://doi.org/10.1016/j.ijbiomac.2025.142299>

507 Yao T, Zeng X, Zou Y, Luo T, Tao X, Xu H (2024) Fabrication of polyvinyl
 508 alcohol/vanillin/Ti3C2Tx/ZnONPs composite film with excellent antimicrobial
 509 properties for pepper preservation. *Food Bioscience* 59: 104175.
 510 <https://doi.org/10.1016/j.fbio.2024.104175>

511 Panda J, Mishra A K, Nandi N B, Mishra B, Rustagi S, Thatoi H, Nath P C, Mohanta Y K
 512 (2026) Microbial-nanobiotechnology for sustainable food preservation, safety, and
 513 security: Current challenges and potential solutions. *Food and Bioproducts Processing*
 514 157: 550-565. <https://doi.org/10.1016/j.fbp.2026.04.002>

515 Vencato A A, Clerici N J, Mendes Juchem A L, Rolla H C, Brandelli A (2025) Nisin
 516 electrospun nanofibers as promising active food packaging. *Journal of Food*
 517 *Engineering* 400: 112643. <https://doi.org/10.1016/j.jfoodeng.2025.112643>

518 Wang R, Xue H, Leng J, Zhang J, Yan Z, Liu X, Feng H, Xiao L, Zhu W (2022) Preparation
 519 and antibacterial properties of hemp cellulose-based material based on Schiff base
 520 between lysine grafted N-halamine and dialdehyde hemp. *Industrial Crops and*
 521 *Products* 176: 114388. <https://doi.org/10.1016/j.indcrop.2021.114388>

522 Wu Y-M, Wang Z-W, Hu C-Y, Nerín C (2018) Influence of factors on release of
 523 antimicrobials from antimicrobial packaging materials. *Critical Reviews in Food*
 524 *Science and Nutrition* 58: 1108-1121.
 525 <https://doi.org/10.1080/10408398.2016.1241215>

526 Jieying S, Tingting L, Caie W, Dandan Z, Gongjian F, Xiaojing L (2024) Paper-based

527 material with hydrophobic and antimicrobial properties: Advanced packaging
 528 materials for food applications. Comprehensive Reviews in Food Science and Food
 529 Safety 23: e13373. <https://doi.org/10.1111/1541-4337.13373>
 530 Zanchettin G, Falk G S, González S Y G, Hotza D (2023) Tutorial review on the processing
 531 and performance of fabrics with antipathogenic inorganic agents. Cellulose 30: 2687-
 532 2712. <https://doi.org/10.1007/s10570-023-05060-8>
 533 Zhang H, Xu M, Wang L, Luo H, Wu S, Gao T, Wu Q, Xu H (2024a) ZnO-incorporated
 534 chitin hydrogels for infected wound therapy. Cellulose 31: 3115-3127.
 535 <https://doi.org/10.1007/s10570-024-05801-3>
 536 K S S, M.P I, G.R R (2019) Mahua oil-based polyurethane/chitosan/nano ZnO composite
 537 films for biodegradable food packaging applications. International Journal of
 538 Biological Macromolecules 124: 163-174.
 539 <https://doi.org/10.1016/j.ijbiomac.2018.11.195>
 540 Liu C, Luo B, Zou Z, Li X, Zhang X, Li Y, Xiong S, Xu Y, Yang Z, Li Y (2025) Robust
 541 Sustainable Interfacial Evaporators from Lignin for Wastewater Treatment. Advanced
 542 Materials 37: e13323. <https://doi.org/10.1002/adma.202513323>
 543 Kong J, Chen H, Li Z, Tang M, Wang Y, Guo Y, Zhang W, An T (2025) Synergistic defect
 544 engineering in β -MnO₂ nanorods for energy-efficient photocatalytic air purification.
 545 Chemical Engineering Journal 522: 167730.
 546 <https://doi.org/10.1016/j.cej.2025.167730>
 547 Sha J, Zhu Z, Lin M, Zhu L, Wang Z, Xiao K (2025) Chitosan/MXene/ ϵ -polylysine based
 548 biodegradable packaging films with synergistic photothermal antimicrobial properties.
 549 Food Packaging and Shelf Life 50: 101544.

550 <https://doi.org/10.1016/j.fpsl.2025.101544>

551 Yang J, Rhim J-W, Jafari S M, Zhang W (2025) Photoactivated multimodal antimicrobial
552 biopolymer films: synergies, innovations, and sustainable intelligent food packaging.
553 Advanced Composites and Hybrid Materials 8. [http://doi.org/10.1007/s42114-025-](http://doi.org/10.1007/s42114-025-01438-3)
554 01438-3

555 Luo L, Cai W, Su W, Wang M, Zhang L, Sun J, Wang J (2025) Synergistic antimicrobial
556 packaging film with photothermal-controlled biocatalytic capability for tangerine
557 preservation. Food Hydrocolloids 160: 110832.
558 <https://doi.org/10.1016/j.foodhyd.2024.110832>

559 Wang X-M, Huang L, Wang Y-J, Xuan L, Li W-W, Tian L-J (2021) Highly efficient near-
560 infrared photothermal antibacterial membrane with incorporated biogenic CuSe
561 nanoparticles. Chemical Engineering Journal 405: 126711.
562 <https://doi.org/10.1016/j.cej.2020.126711>

563 Qi C, Zhang Y, Tu J (2022) Facile synthesis of ϵ -poly-L-lysine-conjugated ZnO@PDA as
564 photothermal antibacterial agents for synergistic bacteria killing and biofilm
565 eradication. Biochemical Engineering Journal 186: 108569.
566 <https://doi.org/10.1016/j.bej.2022.108569>

567 Xu X, Chao Y, Ma X, Zhang H, Chen J, Zhu J, Chen J (2024) A photothermally antibacterial
568 Au@Halloysite nanotubes/lignin composite hydrogel for promoting wound healing.
569 International Journal of Biological Macromolecules 258: 128704.
570 <https://doi.org/10.1016/j.ijbiomac.2023.128704>

571 Ran J, Chen Y, Wang A, Dai Y, Zhang T, Qiu F (2024) Bionic penguin feather wearable
572 textile with coupled insulation for thermal management application. Cellulose 31:

573 9777-9790. <https://doi.org/10.1007/s10570-024-06183-2>

574 Zhang Y, Huang S, Chen Y, Zhang T, Qiu F (2026) Bifunctional cellulose-based membrane
575 with improved mechanical properties for sustainable food packaging. Cellulose.
576 <https://doi.org/10.1007/s10570-026-07096-y>

577 Zhang X, Yang G, Jiang Q, Fan J, Wang S, Chen J (2024b) Carboxymethyl cellulose-based
578 photothermal film: A sustainable packaging with high barrier and tensile strength for
579 food long-term antibacterial protection. International Journal of Biological
580 Macromolecules 276: 133910. <https://doi.org/10.1016/j.ijbiomac.2024.133910>

581 Zhao W, Liang Y, Zhang Y, Deng Y, Fu H, Yuan X, Wang Z, Lu X, Lin B (2025) Active
582 cellulose-based film with synergistic enhanced photothermal antibacterial effects by
583 Fe-doped ZIF-8 and EGCG for efficient litchi preservation. Chemical Engineering
584 Journal 521: 166462. <https://doi.org/10.1016/j.cej.2025.166462>

585 Zhu P, Yang J, Sun F, Wang K, Li H, Peng L (2025) One stone, three birds: Polydopamine-
586 hybridized ZIF-8 for constructing superhydrophobic paper with synergistic
587 photothermal and photodynamic antibacterial activity for active food packaging.
588 Chemical Engineering Journal 522: 167744.
589 <https://doi.org/10.1016/j.cej.2025.167744>

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