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**Plasma-Activated Water and Oregano Essential Oil Nanoliposomes
Integrated into a Hydroxyethyl Cellulose Coating for Microbial
Control of Seafood**

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1 **Abstract:**

2 Plasma-activated water (PAW) is a promising non-thermal antimicrobial system for food
3 preservation, but the limited persistence of reactive oxygen and nitrogen species (RONS) can restrict
4 its prolonged activity on food surfaces. This study developed a hydroxyethyl cellulose (HEC)-based
5 active coating integrating PAW-derived RONS with oregano essential oil nanoliposomes (OEONL)
6 for microbial control of seafood. Among the tested HEC concentrations, 3% (w/v) provided the
7 most favorable balance of water uptake, water retention, and RONS persistence. OEONL exhibited
8 a mean particle size of 102.31 ± 1.46 nm and an encapsulation efficiency of $79.31 \pm 2.86\%$.
9 Nanoliposomal incorporation produced a more homogeneous coating microstructure while largely
10 preserving the principal chemical features of HEC. Incorporation of OEONL also enhanced DPPH
11 radical-scavenging activity in a sample-mass- and extraction-time-dependent manner. In seafood
12 challenge tests, the PAH-OEONL coating suppressed total viable counts (TVC), *Vibrio*
13 *parahaemolyticus*, and *Salmonella* in shrimp meat and golden pompano fillets at both 4 and 25 °C.
14 At 4 °C, it delayed TVC from reaching 7 log CFU/g from approximately day 6 to day 16 in shrimp
15 meat and from day 4 to day 14 in golden pompano fillets, representing a delay of approximately 10
16 days relative to uncoated controls. Antimicrobial activity also remained evident at 25 °C. These
17 findings demonstrate that combining PAW-derived reactive species with nanoliposome-delivered
18 OEO provides a promising active-coating strategy for microbial control of seafood under different
19 storage temperatures.

20 **Keywords:** Plasma-activated water; Oregano essential oil nanoliposomes; Active coating;
21 Seafood; Microbial control

1. Introduction

Plasma-activated water (PAW) has attracted increasing attention as a non-thermal antimicrobial approach for food preservation because it contains a variety of reactive oxygen and nitrogen species (RONS), including hydrogen peroxide, nitrite, nitrate, and other transient reactive species. However, the direct application of liquid PAW to food surfaces may be constrained by rapid runoff, diffusion, and attenuation of reactive species, which can limit the duration of antimicrobial activity during storage. Immobilizing PAW within a three-dimensional hydrogel network offers a potential strategy to retain plasma-derived reactive species at the food surface and regulate their release over time. Plasma-activated hydrogels (PAHs) have been reported to act as reservoirs for plasma-derived reactive species, enabling sustained RONS delivery and prolonged microbial inhibition compared with direct liquid treatment (Chen et al., 2023; Liu et al., 2019). Although PAHs have been extensively investigated for biomedical disinfection and antimicrobial applications, their application in food systems remains relatively limited. Recent studies using PAW–biopolymer coatings for fish preservation have nevertheless demonstrated the potential of such systems as active matrices for controlling microbial growth in perishable foods (Gao et al., 2025).

The performance of a PAH is strongly influenced by the physicochemical characteristics of its polymeric matrix, which govern water retention, structural stability, and the diffusion of incorporated reactive species. Hydroxyethyl cellulose (HEC), a non-ionic, water-soluble cellulose derivative, is particularly suitable for constructing food-oriented hydrogel coatings because of its film-forming ability, hydrophilicity, and capacity to form physically associated three-dimensional networks. Hydrogen-bonding interactions within HEC networks may facilitate the retention of water and dissolved reactive species, thereby modulating their diffusion from the hydrogel matrix (Zhai et al., 2021). However, the influence of HEC concentration on the water uptake, water-retention capacity, and RONS-release behavior of PAW-based hydrogels has not been sufficiently characterized in the context of food preservation. Establishing an appropriate HEC network is therefore important for developing a PAH capable of maintaining localized and sustained antimicrobial activity at food surfaces.

Although PAW-derived RONS provide strong antimicrobial activity, a hydrogel relying primarily on oxidative reactive species offers limited antioxidant functionality. Incorporation of a complementary plant-derived bioactive may therefore broaden the functional properties of PAW-

based coatings. Oregano essential oil (OEO), which is rich in phenolic compounds such as carvacrol and thymol, exhibits well-established antimicrobial and free-radical-scavenging activities. Its antimicrobial action has been associated with disruption of bacterial membrane integrity and increased membrane permeability, whereas its phenolic constituents can donate hydrogen atoms or electrons to neutralize free radicals (Du et al., 2024; Pontes-Quero et al., 2021). Direct incorporation of OEO into hydrophilic hydrogel matrices, however, is hindered by its hydrophobicity, volatility, poor aqueous dispersibility, and tendency toward heterogeneous distribution. Nanoliposomes composed of amphiphilic phospholipid bilayers provide an effective carrier for hydrophobic essential oils by improving their dispersibility in aqueous systems, protecting volatile bioactive compounds, and facilitating their incorporation into hydrophilic matrices (Pontes-Quero et al., 2021). Incorporating OEO in nanoliposomal form may therefore improve its compatibility with the HEC network while introducing complementary antioxidant and antimicrobial functionality into PAW-based hydrogel coatings.

Accordingly, this study aimed to develop an HEC-based active coating integrating PAW-derived reactive species with nanoliposome-delivered OEO for microbial control of seafood. We hypothesized that nanoliposomal OEO would improve its physical integration within the hydrophilic HEC/PAW matrix while providing complementary antioxidant and antimicrobial functions. HEC/PAW hydrogels with different HEC concentrations were first evaluated for water uptake, water retention, and RONS concentration profiles to select a suitable coating matrix. Free OEO and OEONL were then incorporated into the selected formulation and characterized in terms of microstructure, chemical characteristics, thermal behavior, antioxidant activity, and antimicrobial performance. Finally, shrimp meat and golden pompano fillets were used to evaluate microbial control against total viable microorganisms, *Vibrio parahaemolyticus*, and *Salmonella* at 4 and 25 °C.

2. Materials and Methods

2.1 Preparation of plasma-activated water

Plasma-activated water (PAW) was prepared using the dual-discharge system previously developed and optimized by (Chen et al., 2026). Briefly, 2.4 L of deionized water containing 0.019% (w/v) NaCl was placed in a 3-L borosilicate glass beaker and treated using a dual-discharge configuration consisting of an above-liquid electrode and a submerged electrode. Dry air was

supplied as the working gas at a flow rate of 5 L/min. The input voltage was set to 171 V, and plasma treatment was continued for 30 min. Under these optimized conditions, the concentrations of NO₂⁻, NO₃⁻, H₂O₂, and O₃ were 172.11 ± 12.85, 5.11 ± 0.07, 3.25 ± 0.41, and 0.81 ± 0.06 mg/L, respectively (Chen et al., 2026). Freshly prepared PAW was immediately used for preparation of the HEC/PAW hydrogels.

2.2 Preparation of plasma-activated and active composite hydrogels

HEC was added to freshly prepared PAW to obtain 2%, 3%, and 4% (w/v) HEC/PAW hydrogels (PAH), which were stirred at room temperature until homogeneous. The formulations were evaluated for water uptake, water holding capacity, and RONS concentration profiles, and the optimal HEC concentration was selected for subsequent experiments.

Free OEO or OEONL was then incorporated into the selected PAH matrix to prepare PAH-OEO and PAH-OEONL, respectively. The OEO-equivalent concentration was maintained at 1.25 µL/mL in both formulations. An HEC/deionized-water hydrogel served as the HEC control, while HEC/PAW without OEO or OEONL served as the PAH control. Unless otherwise specified, all hydrogels were protected from light and stored at 4 °C until use.

2.3 Characterization of plasma-activated hydrogels

2.3.1 Water uptake capacity

HEC/PAW hydrogel samples containing 2%, 3%, or 4% (w/v) HEC were prepared as 6 cm × 6 cm specimens and dried in a vacuum oven at 50 °C for 24 h. The initial dry mass of each sample was recorded as W₀. The dried samples were then individually immersed in 30 mL of distilled water and incubated at either 4 or 25 °C. At predetermined time intervals, the samples were removed from the water, gently blotted with filter paper to remove excess surface water, and immediately weighed (W_t). Water uptake was calculated according to Eq. (1) (Fawal et al., 2018):

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

Where, W_t was the weight of the swollen hydrogel film at time t, and W₀ was the initial dry weight of the sample. All measurements were performed in triplicate.

The water-uptake profiles at 4 and 25 °C were further fitted using first-order, Peleg, and Weibull models according to Eqs. (2)–(4), respectively:

$$Q_t = Q_e(1 - e^{-kt}) \quad (2)$$

$$Q_t = \frac{t}{k_1 + k_2 t} \quad (3)$$

$$Q_t = Q_e \left(1 - e^{-\left(\frac{t}{\tau}\right)^\beta} \right) \quad (4)$$

Where, Q_t was the water uptake at time t , Q_e was the equilibrium water uptake, k was the first-order swelling rate constant, k_1 and k_2 were the Peleg rate and capacity constants, respectively, τ was the Weibull characteristic time, and β was the Weibull shape parameter.

2.3.2 Water holding capacity

HEC/PAW hydrogels containing 2%, 3%, or 4% (w/v) HEC were used to evaluate water-retention behavior during storage. Samples were stored at either 4 or 25 °C under identical storage conditions. At 25 °C, sample masses were recorded at 0, 8, 16, 36, 48, 60, 72, and 96 h. At 4 °C, measurements were performed daily for 14 days. At each sampling point, the mass of each hydrogel was recorded, and the water holding capacity (WHC) was calculated according to Eq. (5):

$$\text{Water holding capacity} = \frac{W_t}{W_0} \times 100\% \quad (5)$$

Where, W_t was the weight of the hydrogel at time t , and W_0 was the initial weight of the hydrogel. All measurements were performed in triplicate.

The WHC profiles were further fitted using the Weibull, exponential-decay, and double-exponential models according to Eqs. (6)–(8), respectively:

$$W_t = W_e + (W_0 - W_e)e^{-\left(\frac{t}{\alpha}\right)^\beta} \quad (6)$$

$$W_t = W_e + (W_0 - W_e)e^{-kt} \quad (7)$$

$$W_t = Ae^{-k_1 t} + Be^{-k_2 t} + C \quad (8)$$

Where, W_t was the WHC at time t , W_0 was the initial WHC, W_e was the equilibrium WHC. In the Weibull model, α was the characteristic time parameter, β was the shape parameter. In the exponential-decay model, k was the apparent water-loss rate constant. In the double-exponential model, k_1 , and k_2 were the apparent rate constants associated with the fast and slow water-loss components, respectively, while A and B represented their corresponding contributions and C represented the asymptotic residual WHC.

2.3.3 RONS concentration profiles

A 10% (v/v) ethanol solution was used as the release medium according to Wang et al. (2022). HEC/PAW hydrogels (8 mL; 2%, 3%, or 4% HEC) were placed in contact with 1 mL of release

medium and maintained statically at 4 or 25 °C. At 25 °C, the medium was sampled at 2, 8, 15, 22, 40, and 120 h; at 4 °C, sampling was performed every 3 days. After each sampling, an equal volume of fresh medium was added.

H₂O₂, NO₂⁻, and NO₃⁻ concentrations were determined using previously reported methods with slight modifications (Gao et al., 2025; Nasiru et al., 2024; Zhang et al., 2024). The resulting profiles represented the detectable RONS concentrations in the external medium over time and were interpreted as indicators of RONS persistence and apparent release behavior rather than cumulative release. All measurements were performed in triplicate.

2.4 Preparation of oregano essential oil nanoliposome suspension

Oregano essential oil nanoliposomes (OEONL) were prepared according to a previously reported method (Nami et al., 2024), with slight modifications. Briefly, 2 g of soybean lecithin (CP grade; Shanghai Meryer Biochemical Technology Co., Ltd., China) was dispersed in 38 mL of distilled water and continuously stirred at 300 rpm for 5 h at room temperature to obtain a homogeneous lecithin dispersion. Subsequently, 4 mL of oregano essential oil (OEO; Suzhou Geruite Pharmaceutical Technology Co., Ltd., China) was added to the lecithin dispersion and mixed thoroughly. The resulting mixture was ultrasonicated using an ultrasonic processor (Shanghai Shangpu Instrument Equipment Co., Ltd., China) at 40 kHz and 40% power for 600 s in a pulsed mode of 1 s on and 1 s off. The sample was maintained under cooling conditions throughout ultrasonication to minimize temperature elevation and volatilization of OEO. The resulting OEONL suspension was transferred to light-protected containers and stored at 4 °C until further use.

2.5 Evaluation of the antibacterial activity of oregano essential oil

The antibacterial activity of OEO was evaluated against *Salmonella* ATCC 14028 and *Vibrio parahaemolyticus* ATCC 17802. Bacterial concentrations were estimated using OD₆₀₀–viable count calibration curves established according to Beal et al. (2020), and suspensions were adjusted to 1×10⁵ CFU/mL before testing.

The minimum inhibitory concentration (MIC) was determined by the broth microdilution method in 96-well plates. OEO was solubilized with a small amount of dimethyl sulfoxide (DMSO) and diluted with broth to 20 µL/mL. An aliquot (180 µL) of this solution was mixed with 180 µL of broth in the first well to give a nominal OEO concentration of 10 µL/mL, followed by two-fold serial dilution. After dilution, 10 µL of bacterial suspension was added to each well containing 180

μL of test solution. A DMSO solvent control was included. After incubation at 37 °C for 18 ± 2 h, the lowest concentration showing no visible growth was recorded as the MIC. For minimum bactericidal concentration (MBC) determination, 50 μL from wells without visible growth was plated on agar and incubated at 37 °C for 24 h; the lowest concentration producing no colonies was recorded as the MBC.

2.6 Characterization of nanoliposome suspension

OEONL was characterized according to Azizi et al. (2024) with slight modifications. Particle size and polydispersity index (PDI) were measured using a laser particle size analyzer (SALD-2101, Shimadzu, Japan), and zeta potential was determined using a Zetasizer Nano ZS (Malvern Instruments, UK).

Encapsulation efficiency (EE%) was determined by UV spectrophotometry according to Pabast et al. (2018). Unencapsulated OEO was separated by Amicon ultrafiltration, and the retained nanoliposomal fraction was disrupted for determination of encapsulated phenolic-equivalent content. Total phenolic-equivalent content was determined after disrupting the initial OEONL suspension with Triton X-100. EE was calculated according to Eq. (9):

$$EE\% = \frac{C_{encap}}{C_{total}} \times 100 \quad (9)$$

where C_{encap} and C_{total} represented the encapsulated and total phenolic-equivalent concentrations, respectively.

2.7 Structural characterization of functional hydrogels

2.7.1 Microstructural analysis

The microstructure of the hydrogel samples was examined by scanning electron microscopy (SEM). Prior to SEM observation, the hydrogel samples were freeze-dried using a vacuum freeze dryer (SCIENTZ-10N, Ningbo Scientz Biotechnology Co., Ltd., China). The dried samples were mounted on SEM stubs using conductive adhesive tape and sputter-coated with a thin layer of gold. The microstructures were then observed using a scanning electron microscope (EVO 18, Carl Zeiss, Germany) at an accelerating voltage of 5 kV.

2.7.2 Fourier transform infrared spectroscopy analysis

Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) was performed according to the method described by Miao et al. (2022) with slight modifications. All

samples were dried prior to analysis. FTIR spectra were recorded using a Nicolet 6700 FTIR spectrometer (Thermo Fisher Scientific, USA) over a wavenumber range of 4000–650 cm⁻¹ at a resolution of 4 cm⁻¹, with 32 scans accumulated for each spectrum.

2.7.3 Thermogravimetric analysis

Thermogravimetric analysis (TGA) was performed according to the method of Miao et al. (2022) with slight modifications. Approximately 5 mg of each dried sample was analyzed using a TGA2 thermogravimetric analyzer (Mettler Toledo, USA). Samples were heated from 40 to 600 °C at a heating rate of 20 °C/min under a nitrogen atmosphere at a flow rate of 50 mL/min. The mass loss was recorded as a function of temperature, and derivative thermogravimetric (DTG) curves were obtained to determine the temperature corresponding to the maximum mass-loss rate (T_{max}). The temperatures corresponding to 5%, 10%, and 50% mass loss (T₅, T₁₀, and T₅₀, respectively), as well as the residual mass at 600 °C (R₆₀₀), were also determined.

2.8 DPPH radical-scavenging activity

DPPH radical-scavenging activity was determined according to Yu et al. (2022) with slight modifications. Four formulations were tested: C (HEC/deionized water), PAH (HEC/PAW), PAH-OEO, and PAH-OEONL. Briefly, 60 mg of each sample was extracted with 5 mL of 10% (v/v) ethanol in the dark at room temperature for 24 h. The supernatant (2 mL) was mixed with 2 mL of 0.2 mmol/L DPPH solution in ethanol and incubated in the dark for 1 h. Absorbance was measured at 517 nm, and scavenging activity was calculated according to Eq. (10):

$$DPPH\ radical\ scavenging\ activity(\%) = \frac{A_0 - A_1}{A_0} \times 100 \quad (10)$$

where A₀ and A₁ were the absorbance values of the DPPH solution without and with sample extract, respectively.

To assess the effects of sample amount and extraction time, 10–60 mg of PAH-OEONL was extracted under the same conditions for 4 or 24 h and analyzed using the same DPPH assay.

2.9 Microbiological analysis

Golden pompano (*Trachinotus ovatus*) and whiteleg shrimp (*Litopenaeus vannamei*) were purchased from Hema Fresh Market (Wuxi, China) and transported to the laboratory under refrigerated conditions. Golden pompano were cut into approximately 30 g fillets, and shrimp meat of similar size was selected.

Seafood samples were separately inoculated with *Salmonella* ATCC 14028 or *Vibrio parahaemolyticus* ATCC 17802 suspensions (approximately 1×10^5 CFU/mL). A total of 20 μ L of bacterial suspension was distributed over 20 surface locations per sample, followed by air-drying for 30 min under sterile conditions. Samples were then divided into uncoated control, PAH, PAH-OEO, and PAH-OEONL groups. Coated samples were immersed in the corresponding hydrogel until the surface was uniformly covered and then stored at 4 or 25 °C.

Microbial analyses were performed on days 0, 2, 4, 6, 8, 10, 12, 14, and 16 at 4 °C and at 24-h intervals at 25 °C. At each sampling point, 5 g of sample was homogenized with 45 mL of sterile physiological saline and serially diluted ten-fold. Aliquots (100 μ L) were spread onto Plate Count Agar (PCA; Zhongshan Baiwei, China) for TVC, Xylose Lysine Deoxycholate agar (XLD; Zhongshan Baiwei, China) for *Salmonella*, and Thiosulfate-Citrate-Bile Salts-Sucrose agar (TCBS; Beijing Land Bridge, China) for *V. parahaemolyticus*. Plates were incubated at 36 °C for 48 h, and results were expressed as $\log_{10}$ CFU/g.

2.10 Statistical analysis

Unless otherwise specified, data are presented as mean $\pm$ standard deviation (SD) from three independent replicates. Statistical analyses were performed using IBM SPSS Statistics software. Differences among treatment groups at the same sampling time were evaluated by one-way analysis of variance (ANOVA), followed by Duncan's multiple range test. For measurements evaluated over storage time, differences among sampling times within the same treatment were analyzed separately using one-way ANOVA followed by Duncan's multiple range test. Microbial counts were expressed as $\log_{10}$ CFU/g before statistical analysis. Differences were considered statistically significant at $p < 0.05$. Graphs were generated using Origin 2024.

3. Results and Discussion

3.1 Performance of plasma-activated hydrogels

3.1.1 Water uptake capacity

The HEC/PAW hydrogels exhibited a typical two-stage water-uptake profile at both 4 and 25 °C, characterized by an initial rapid increase followed by a gradual approach to equilibrium (Fig. 1A and B). At 4 °C, equilibrium was reached after approximately 60–70 min, whereas the corresponding equilibration time decreased to approximately 25–30 min at 25 °C. The faster water uptake at the higher temperature may be attributed to enhanced water diffusion and increased

mobility of the polymer chains, facilitating hydration and relaxation of the hydrogel network (Cui et al., 2022).

HEC concentration significantly affected the equilibrium water uptake of the hydrogels. Among the tested formulations, the 3% (w/v) HEC hydrogel exhibited the highest equilibrium water uptake at both temperatures, whereas lower values were observed for the 2% and 4% formulations. This non-linear dependence on HEC concentration may reflect a balance between network integrity and accessibility to water. At a relatively low HEC concentration (2%, w/v), insufficient polymer–polymer interactions may result in a less stable network, whereas increasing the concentration to 4% may produce a denser and more entangled structure that restricts water penetration and network expansion (Jamlang et al., 2019; Li et al., 2021). The intermediate HEC concentration therefore appeared to provide a network structure more favorable for hydration.

Kinetic modeling further supported the temperature-dependent swelling behavior (Table 1). The first-order, Peleg, and Weibull models all provided good fits to the experimental data, with R^2 values above 0.991. Among them, the Weibull model showed the best overall fitting performance, with R^2 values ranging from 0.9958 to 0.9989. Increasing the temperature also increased the apparent first-order swelling rate constant (k). For example, the k value of the 3% (w/v) HEC hydrogel increased from 0.091 min^{-1} at 4°C to 0.138 min^{-1} at 25°C , while the Weibull characteristic time (τ) decreased from 9.86 to 7.92 min. These kinetic parameters were consistent with the experimentally observed acceleration of water uptake at the higher temperature.

3.1.2 Water holding capacity

The water holding capacity (WHC) of the HEC/PAW hydrogels gradually decreased with storage time at both 4°C and 25°C (Fig. 1C and D). The rate of water loss was relatively high during the initial stage and subsequently decreased as storage progressed, indicating a gradual transition toward a more stable residual water content. This behavior may be associated with progressive water loss from the hydrogel network, followed by increasingly restricted removal of water retained through polymer–water interactions (Gao et al., 2021). At 4°C , all formulations retained more than 55% of their initial water content after 14 days. At 25°C , the WHC approached approximately 43%–48% after 100 h. These results demonstrate that the HEC/PAW hydrogels retained a substantial proportion of water over prolonged storage, including under the higher-temperature condition.

HEC concentration significantly affected the water-retention behavior of the hydrogels.

Consistent with the water-uptake results, the 3% (w/v) HEC formulation exhibited the highest WHC throughout the evaluated storage period at both temperatures. This behavior may reflect a favorable balance between polymer network integrity and water mobility within the hydrogel. At lower HEC concentration, weaker intermolecular association may reduce the ability of the network to retain water, whereas excessive polymer concentration may increase chain entanglement and restrict effective hydration within the matrix (Li et al., 2021). The intermediate HEC concentration therefore appeared to provide more favorable conditions for maintaining water within the hydrogel network.

The WHC profiles were further fitted using Weibull, exponential-decay, and double-exponential models (Table 2). All three models adequately described the experimental data, with R^2 values above 0.984, although their fitting performance varied with HEC concentration and storage temperature. Overall, the fitted parameters were consistent with the experimentally observed water-retention behavior of the 3% (w/v) HEC hydrogel, which showed a relatively high residual WHC and lower apparent water-loss rate constants than the 2% (w/v) and 4% (w/v) formulations at both temperatures. Together with its favorable water-uptake behavior, these results indicate that the 3% HEC formulation provided a suitable balance between hydration capacity and water retention.

3.1.3 Sustained release of RONS

To characterize the release and persistence of PAW-derived RONS in the hydrogel systems, H_2O_2 , NO_2^- , and NO_3^- concentrations in the surrounding medium were monitored at 4 and 25 °C. The detectable H_2O_2 concentration initially increased and subsequently declined at both temperatures (Fig. 2A and B). For the 3% HEC formulation, H_2O_2 reached a maximum concentration of 3.11 ± 0.09 mg/L at approximately day 9 at 4 °C and 3.04 ± 0.07 mg/L at 15 h at 25 °C. The substantially earlier maximum observed at 25 °C suggests that elevated temperature accelerated the overall processes governing H_2O_2 transport and transformation. Because H_2O_2 was simultaneously released from the hydrogel and depleted in the surrounding medium, the subsequent decline in its detectable concentration likely reflected a shift in the balance between these competing processes rather than cessation of release alone.

A similar time-dependent profile was observed for NO_2^- (Fig. 2C and D). In the 3% (w/v) HEC hydrogel, the detectable NO_2^- concentration reached a maximum of 18.03 ± 0.23 mg/L at day 12 at 4 °C and 18.21 ± 0.35 mg/L at 40 h at 25 °C, followed by a gradual decline. As a relatively reactive nitrogen species, NO_2^- can undergo further chemical transformation during storage, including

oxidative conversion to more stable nitrogen species such as NO_3^- (Zhou et al., 2023). Therefore, the decrease in detectable NO_2^- at later stages likely resulted from the combined effects of continued release, chemical transformation, and depletion in the surrounding medium.

In contrast, the detectable NO_3^- concentration increased progressively during storage and gradually approached a relatively stable level (Fig. 2E and F), consistent with the greater persistence of NO_3^- compared with H_2O_2 and NO_2^- . The 3% (w/v) HEC formulation exhibited the highest overall NO_3^- concentrations among the tested hydrogels, reaching 77.11 ± 0.12 mg/L at 4 °C and 73.44 ± 0.27 mg/L at 25 °C. The progressive accumulation of NO_3^- may reflect both its release from the HEC/PAW matrix and the transformation of less stable nitrogen species during storage. The favorable water uptake and water-retention characteristics of the 3% HEC hydrogel may help maintain a hydrated environment for PAW-derived species and enable their prolonged transfer from the polymer network into the surrounding medium (Sabaghi et al., 2022). Taken together with the water-uptake and water-retention results, the RONS profiles indicate that the 3% HEC formulation provided a suitable matrix for maintaining and gradually delivering PAW-derived reactive species and was therefore selected for subsequent incorporation of OEO and OEONL.

3.2 Physicochemical properties of OEONL and antibacterial activity of OEO

The physicochemical characteristics of oregano essential oil nanoliposomes (OEONL) and the antibacterial activity of free OEO against the tested foodborne pathogens are summarized in Table 3. The encapsulation efficiency (EE) of OEONL was $79.31 \pm 2.86\%$, indicating that a substantial proportion of OEO was successfully incorporated into the nanoliposomes. Liposomes possess an amphiphilic structure consisting of an aqueous core surrounded by one or more phospholipid bilayers, allowing hydrophobic compounds such as OEO to associate predominantly with the hydrophobic region of the lipid bilayer. Comparable encapsulation efficiencies have been reported for essential-oil-loaded nanoliposomes, supporting the suitability of phospholipid vesicles as carriers for hydrophobic bioactive compounds (Tometri et al., 2020).

Particle size and polydispersity index (PDI) were used to characterize the size distribution of OEONL. The mean particle size was 102.31 ± 1.46 nm (Table 3), confirming the formation of nanoscale vesicles. The relatively small particle size may facilitate the dispersion of OEONL within the continuous aqueous phase of the HEC/PAW hydrogel matrix, consistent with previous reports on essential-oil-loaded nanoliposomes (Eslamian Amiri et al., 2021; Nami et al., 2024). The PDI of

OEONL was 0.264 ± 0.014 (well below the broadly accepted threshold of 0.3), indicating a relatively narrow particle-size distribution and a comparatively homogeneous vesicle population (Nami et al., 2024).

The zeta potential of OEONL was -2.82 ± 0.03 mV, indicating a slightly negative surface charge, which may be associated with ionizable groups of the phospholipid components (Pabast et al., 2018). The low absolute zeta-potential value suggests that electrostatic repulsion was unlikely to be the primary mechanism maintaining dispersion stability. Nevertheless, zeta potential alone does not fully determine the physical stability of liposomal systems, which can also be influenced by phospholipid composition, vesicle structure, particle-size distribution, and the surrounding continuous phase (Abdollahzadeh et al., 2023). Following incorporation into the viscous HEC hydrogel matrix, reduced vesicle mobility may further limit particle–particle contact and thereby help restrict aggregation, although this effect would require direct stability measurements for confirmation (Grijalvo et al., 2016).

Free OEO exhibited both inhibitory and bactericidal activity against *Vibrio parahaemolyticus* and *Salmonella*. The minimum inhibitory concentration (MIC) was 0.625 $\mu\text{L/mL}$ for both tested bacteria. In contrast, differences were observed in the minimum bactericidal concentration (MBC): the MBC against *V. parahaemolyticus* was 0.625 $\mu\text{L/mL}$, whereas that against *Salmonella* was 1.25 $\mu\text{L/mL}$. These results indicate that, under the present experimental conditions, *V. parahaemolyticus* was more susceptible than *Salmonella* to the bactericidal activity of OEO.

The antibacterial activity of OEO is generally attributed to its phenolic constituents, particularly carvacrol and thymol. Owing to their lipophilic nature, these compounds can interact with bacterial membranes, alter membrane permeability and integrity, and promote leakage of intracellular constituents, ultimately impairing cell viability (Du et al., 2024; Eslamian Amiri et al., 2021). The observed antibacterial activity of free OEO against both tested pathogens, together with the successful encapsulation of OEO in nanoscale liposomes, supports the subsequent incorporation of OEONL into the HEC/PAW coating system for microbial control of seafood.

3.3 Physicochemical properties of plasma-activated hydrogels

3.3.1 Microstructural analysis

SEM images of the freeze-dried hydrogels are shown in Fig. 3A–D. The control HEC hydrogel exhibited a loose and irregular porous morphology, whereas PAH showed a more compact and

continuous structure with clearer pore boundaries, suggesting that PAW incorporation altered the organization of the HEC matrix (Ahmadi et al., 2022).

PAH-OEO displayed a rougher and more heterogeneous morphology, likely related to the poor miscibility of hydrophobic OEO with the hydrophilic HEC/PAW matrix (Iqbal et al., 2023). In contrast, PAH-OEONL exhibited a more uniform and compact morphology. Nanoliposomal encapsulation may have improved the dispersion of OEO within the aqueous hydrogel matrix, thereby reducing phase heterogeneity. These observations are consistent with improved physical integration of OEO following nanoliposomal incorporation (Mourtas et al., 2008).

3.3.2 ATR-FTIR analysis

The ATR-FTIR spectra of the hydrogel formulations are shown in Fig. 3E. The HEC hydrogel exhibited characteristic polysaccharide absorption bands at approximately 1412.7, 1187.4, and 988.4 cm^{-1} , mainly associated with C–H deformation and C–O/C–O–C vibrations (Fawal et al., 2018). A band near 1585.5 cm^{-1} was also observed but was not specifically assigned because of possible overlapping contributions.

The overall HEC spectral profile was largely preserved after incorporation of PAW, OEO, and OEONL. Only minor peak-position variations were observed, which, given the spectral resolution of 4 cm^{-1} , were insufficient to indicate specific changes in intermolecular interactions. No distinct new band appeared in the 1700–1740 cm^{-1} carbonyl region after PAW incorporation. Similarly, OEO- and phospholipid-associated bands were not clearly resolved in PAH-OEO and PAH-OEONL, likely because of their relatively low contents and spectral overlap with the HEC matrix (Iqbal et al., 2023; Pruchnik et al., 2021).

Overall, the preservation of the principal HEC bands and absence of prominent new spectral features indicate no readily detectable modification of the HEC backbone or formation of new covalent structures. Together with the SEM observations (Fig. 3A–D), these results are consistent with the physical incorporation of OEO and OEONL within the HEC/PAW matrix.

3.3.3 Thermal stability

As shown in Fig. 4A and B, all hydrogel formulations exhibited a multistage thermal degradation pattern. The initial mass loss below approximately 150 °C was mainly associated with the removal of residual free and physically retained water, whereas the major degradation stage centered near 290–300 °C was attributed primarily to thermal decomposition and depolymerization

of the HEC polysaccharide backbone. At higher temperatures, further degradation and carbonization of the remaining polymeric components contributed to the formation of residual char.

As summarized in Table 4, the PAH formulation exhibited lower $T_{5\%}$ and $T_{10\%}$ values than the pristine HEC hydrogel, decreasing from 101.03 and 162.48 °C to 90.40 and 148.06 °C, respectively. Because $T_{5\%}$ and part of the $T_{10\%}$ region overlapped with the temperature range associated with moisture loss, these decreases are more appropriately interpreted as changes in the early mass-loss behavior rather than as direct evidence of marked destabilization of the HEC backbone. This phenomenon might be intrinsically linked to the PAW-derived RONS, which modified the hydration state of the HEC chains, thereby facilitating earlier moisture release (Krol-Kilinska et al., 2024; Owusu-Ware et al., 2016; Wong et al., 2023). In contrast, the maximum degradation temperature (T_{max}) of PAH remained very close to that of the control HEC hydrogel (297.33 vs. 296.17 °C), while $T_{50\%}$ decreased only moderately from 313.28 to 309.65 °C. These results indicate that incorporation of PAW had only a limited effect on the principal thermal decomposition region of the HEC matrix.

Following incorporation of OEO and OEONL, further decreases were observed in $T_{10\%}$, $T_{50\%}$, and R_{600} . The $T_{50\%}$ values decreased to 306.30 °C for PAH-OEO and 306.79 °C for PAH-OEONL, while T_{max} remained within a relatively narrow range of 293.17 – 295.33 °C. The magnitude of the maximum mass-loss rate increased from 0.512%·°C⁻¹ for PAH to 0.617%·°C⁻¹ for PAH-OEO and 0.880%·°C⁻¹ for PAH-OEONL. Meanwhile, R_{600} decreased progressively to 29.31% and 28.02%, respectively. These changes likely reflected the contribution of additional thermally labile components, including volatile OEO constituents and phospholipid components of the nanoliposomes, which underwent volatilization and decomposition during heating.

Overall, incorporation of PAW, OEO, and OEONL altered the early-stage mass-loss behavior and reduced the final char yield, while only modestly shifting the principal thermal degradation region of the HEC matrix. The $T_{50\%}$ values of the OEO- and OEONL-containing hydrogels remained above 306 °C, indicating that substantial thermal decomposition occurred at temperatures far above those relevant to their intended application as seafood coatings.

3.4 DPPH radical-scavenging activity

The DPPH radical-scavenging assay was used to evaluate the hydrogen-donating and free-radical-scavenging capacity of the hydrogel formulations (Kanatt et al., 2008). As shown in Fig. 5A,

the pristine HEC and PAH hydrogels exhibited only limited DPPH radical-scavenging activity (approximately 2–3%), with no significant difference between the two groups ($p > 0.05$). These results indicate that HEC possessed negligible radical-scavenging activity under the tested conditions and that incorporation of PAW did not significantly enhance the DPPH scavenging capacity of the hydrogel matrix (Yu et al., 2022). In contrast, incorporation of free OEO markedly increased the DPPH radical-scavenging activity of the PAH-OEO hydrogel to approximately 47%, consistent with the antioxidant activity of phenolic constituents present in OEO.

The PAH-OEONL formulation exhibited higher DPPH radical-scavenging activity than PAH-OEO ($p < 0.05$). The enhanced scavenging activity may be associated with the more homogeneous incorporation of nanoliposomal OEO within the hydrophilic HEC/PAW matrix, as suggested by the microstructural observations (Fig. 3A-D), potentially improving the accessibility of OEO-derived antioxidant constituents to the surrounding medium. However, the observed enhancement likely reflects the combined effects of OEO encapsulation, dispersion, and availability within the assay system rather than a change in the intrinsic antioxidant activity of OEO itself.

As shown in Fig. 5B, the DPPH radical-scavenging activity of PAH-OEONL exhibited clear sample-mass- and incubation-time-dependent behavior. At 4 h, increasing the hydrogel mass from 10 to 60 mg increased the scavenging activity from 24.37% to 67.27% ($p < 0.05$), consistent with the greater amount of OEO-derived antioxidant constituents present at higher hydrogel doses. At a given sample mass, DPPH scavenging also increased progressively with incubation time. This time-dependent response may reflect the gradual availability of antioxidant constituents from the composite matrix together with the kinetics of their reaction with DPPH radicals (Eid et al., 2022). Overall, these results demonstrate that incorporation of OEONL substantially enhanced the in vitro radical-scavenging capacity of the HEC/PAW hydrogel and provided a complementary antioxidant functionality to the predominantly antimicrobial PAW-based system.

3.5 Antimicrobial efficacy in seafood models

The antimicrobial efficacy of the different hydrogel coatings was evaluated by monitoring total viable counts (TVC), *Vibrio parahaemolyticus*, and *Salmonella* in artificially inoculated shrimp meat and golden pompano fillets during storage at 4 and 25 °C (Fig. 6). Storage temperature markedly affected microbial development. At 4 °C, the active coatings initially reduced or strongly suppressed microbial populations, followed by gradual regrowth during prolonged storage, whereas

microbial proliferation occurred much more rapidly at 25 °C.

At 4 °C, PAH treatment clearly delayed the increase in TVC compared with the uncoated control (Fig. 6A and B). In shrimp meat, the TVC of the control exceeded 7 log CFU/g by day 6, whereas the PAH-coated samples reached this level at approximately day 10. In golden pompano fillets, the corresponding time was extended from approximately day 4 in the control to day 8 in the PAH group. This inhibitory effect may be associated with PAW-derived reactive species, including H₂O₂ and other reactive oxygen and nitrogen species, which can damage microbial cellular components and impair cell viability (Tang et al., 2025; Thirumdas et al., 2018).

Incorporation of OEO further strengthened microbial inhibition. At 4 °C, PAH-OEO and PAH-OEONL maintained substantially lower TVC than both the control and PAH groups throughout storage, with PAH-OEONL generally showing the lowest numerical counts. Based on the commonly used TVC criterion of 7 log CFU/g for microbiological spoilage of seafood (Azizi et al., 2024; Nagarajan et al., 2021), the uncoated shrimp meat and golden pompano fillets reached this level at approximately days 6 and 4, respectively, whereas the PAH-OEONL-treated samples did not reach this level until approximately days 16 and 14. Thus, PAH-OEONL delayed the development of high TVC by approximately 10 days under refrigerated storage.

The active coatings also markedly inhibited the two inoculated foodborne pathogens (Fig. 6C - F). At 4 °C, *V. parahaemolyticus* and *Salmonella* populations in the OEO-containing coating groups decreased substantially during the early stage of storage and subsequently increased only gradually. On day 6, PAH-OEONL reduced *V. parahaemolyticus* and *Salmonella* populations in shrimp meat by approximately 3.69 and 3.48 log₁₀ CFU/g, respectively, relative to the uncoated control. Similar reductions were observed in golden pompano fillets, reaching approximately 3.73 log₁₀ CFU/g for *V. parahaemolyticus* and 3.51 log₁₀ CFU/g for *Salmonella*. These results demonstrate effective suppression of both foodborne pathogens in the two seafood matrices.

The antimicrobial effect remained evident under the more intensive microbial-growth conditions at 25 °C (Fig. 6G - L). After 1 day of storage, TVC in the uncoated shrimp meat and golden pompano fillets had increased to 8.43 and 9.17 log CFU/g, respectively, whereas the corresponding counts in PAH-OEONL-treated samples remained at 5.89 and 6.07 log CFU/g. PAH-OEONL also maintained lower populations of *V. parahaemolyticus* and *Salmonella* than the uncoated controls at day 1, demonstrating that the coating retained substantial antimicrobial activity

even under conditions favoring rapid microbial proliferation. Although microbial populations increased further by day 2, OEO-containing coatings continued to exhibit lower counts than PAH alone.

The antimicrobial activity of the composite coatings likely resulted from the complementary contributions of PAW-derived reactive species and OEO-derived antimicrobial compounds. Carvacrol and thymol, major phenolic constituents of OEO, can interact with bacterial membranes, disrupt membrane integrity and permeability, and impair cellular homeostasis (Du et al., 2024; Pinto et al., 2024). Nanoencapsulation may additionally facilitate the incorporation and retention of volatile OEO components within the hydrophilic hydrogel matrix (Pontes-Quero et al., 2021; Yammine et al., 2023). Overall, the HEC/PAW hydrogel provided measurable baseline antimicrobial activity, whereas incorporation of OEO produced substantially stronger microbial inhibition. The OEO-containing formulations, particularly PAH-OEONL, effectively delayed TVC development and suppressed *V. parahaemolyticus* and *Salmonella* in both seafood models at 4 and 25 °C.

4. Conclusion

An HEC-based active coating integrating PAW-derived reactive species with free OEO or OEONL was developed for microbial control of seafood. Among the tested formulations, 3% (w/v) HEC provided the most favorable balance of water uptake, water retention, and RONS persistence and was selected as the coating matrix.

Incorporation of OEO improved the antioxidant and antimicrobial properties of the PAW-based hydrogel. Nanoliposomal incorporation resulted in a more homogeneous microstructure, while ATR-FTIR indicated that the principal chemical features of HEC were largely preserved. The OEO-containing coatings showed strong microbial inhibition, with PAH-OEONL generally producing the lowest numerical counts. PAH-OEONL effectively suppressed TVC, *Vibrio parahaemolyticus*, and *Salmonella* in shrimp meat and golden pompano fillets at both 4 and 25 °C. At 4 °C, it delayed the time required for TVC to reach 7 log CFU/g by approximately 10 days relative to the uncoated controls. Antimicrobial activity also remained evident at 25 °C.

Overall, combining PAW-derived reactive species with nanoliposome-delivered OEO shows promise as an active-coating strategy for microbial control of seafood. Further studies should assess sensory quality, oxidative stability, coating stability, and performance under commercial storage

conditions.

Credit authorship contribution statement

Min Zhou: Carried out the experiments and analytical methods. Writing-original draft; Data curation; **Haiying Chen:** Conceived and designed the study; participated in the planning, supervision and financing of the study. **Tao Wang:** Provided auxiliary support during the experiment. **Lingjun Wei:** Previous literature investigation and research work. **Ning Dai:** Writing-review and editing. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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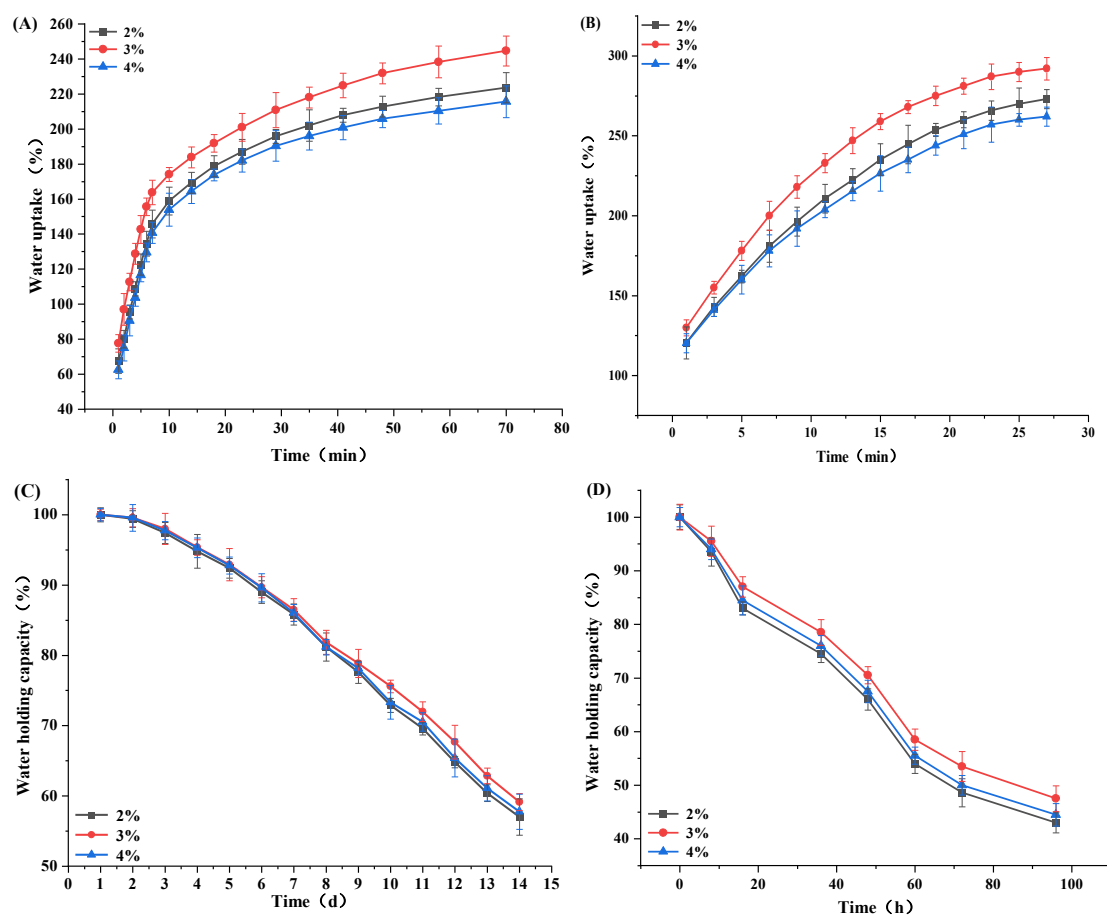
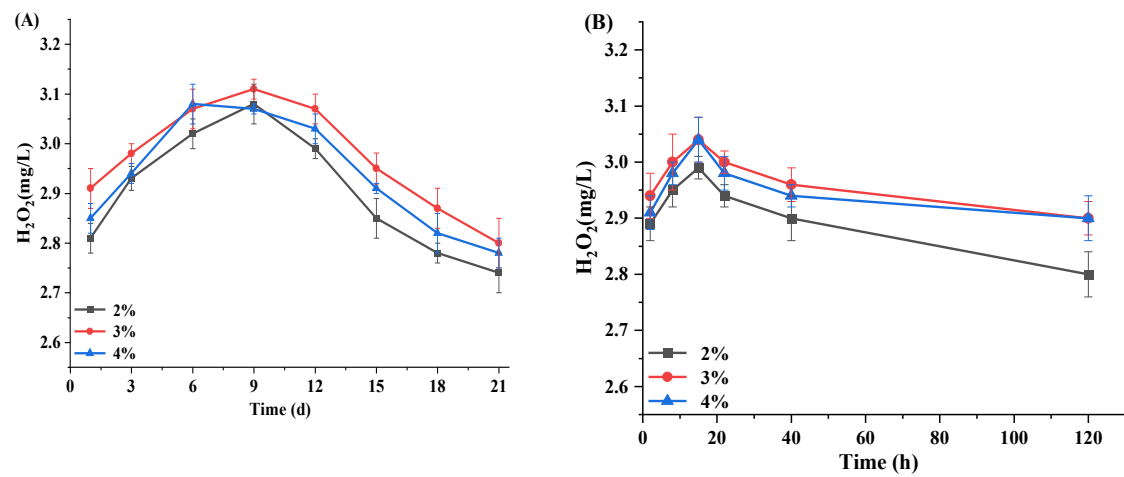


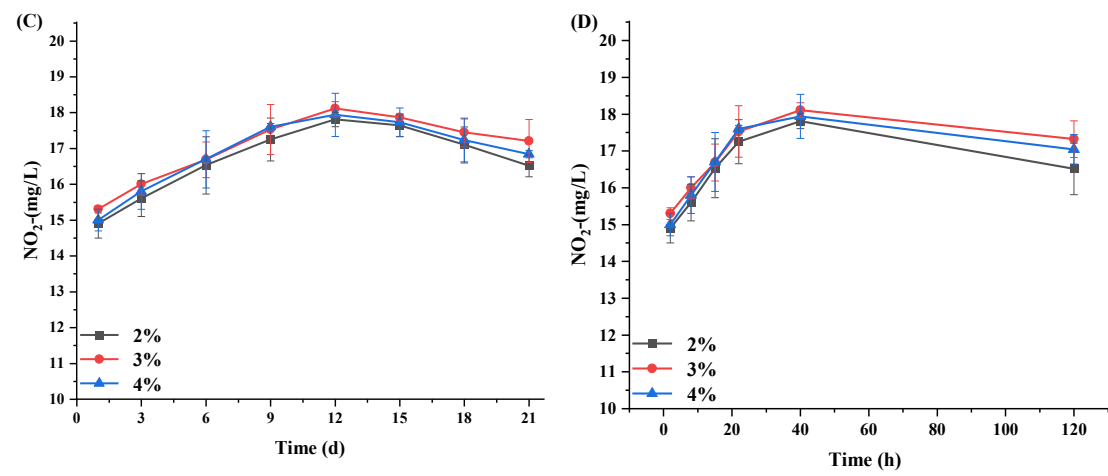
Fig 1 The water uptake at 4 °C (A) and 25 °C (B) and the water holding capacity at 4 °C (C) and 25 °C (D) of HEC/PAW hydrogels with different HEC concentrations (2%, 3%, 4%, w/v).

Note: HEC, Hydroxyethyl cellulose; PAW, Plasma-activated water.

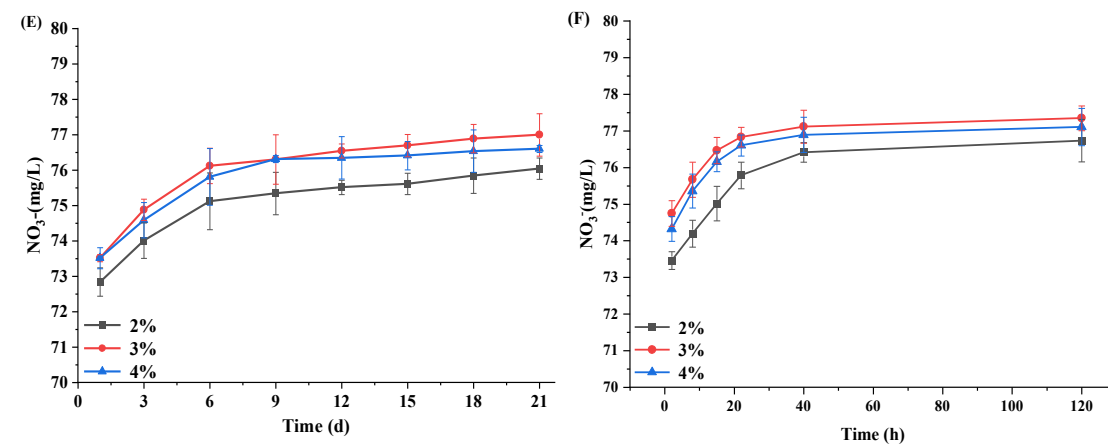
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729 **Fig 2** Release profiles of RONS in HEC/PAW hydrogels with different HEC concentrations
730 (2%, 3%, 4%, w/v): H_2O_2 at 4 °C (A) and 25 °C (B); NO_2^- at 4 °C (C) and 25 °C (D);
731 NO_3^- at 4 °C (E) and 25 °C (F).

732 Note: HEC, Hydroxyethyl cellulose; PAW, Plasma-activated water.

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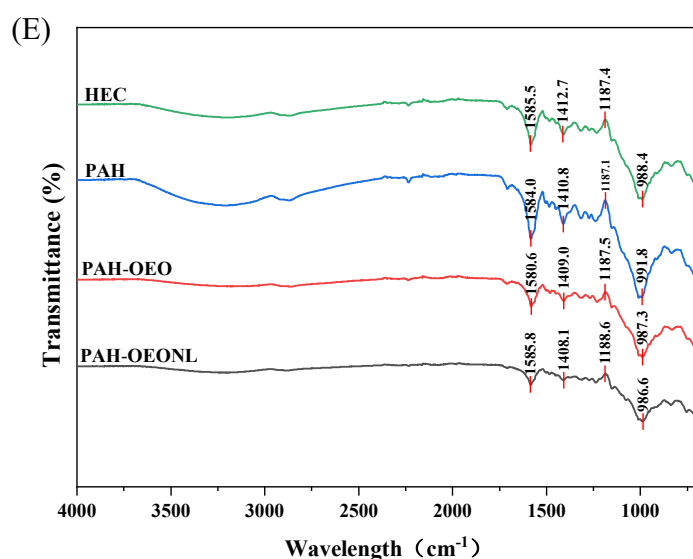
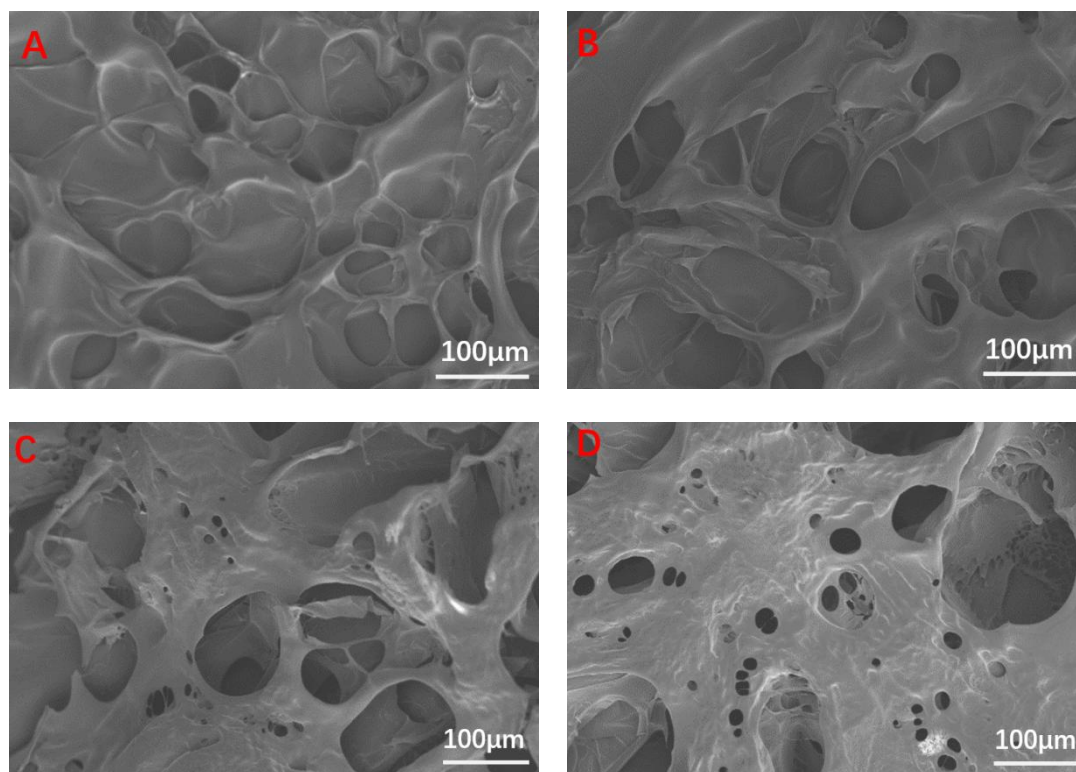


Fig 3 Micromorphology (A-D) and FTIR spectra (E) of hydrogels: (A) HEC with deionized water; (B) PAH; (C) PAH-OEO; (D) PAH-OEONL.
 Note: HEC, hydroxyethyl cellulose; PAH, HEC hydrogel prepared with plasma-activated water; OEO, oregano essential oil; OEONL, oregano essential oil nanoliposomes.

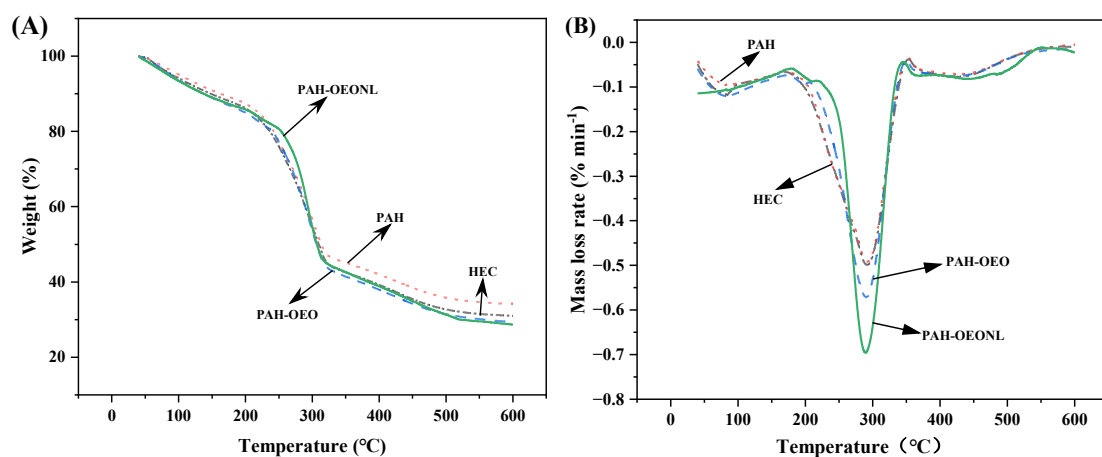


Fig 4 TGA (A) and DTG (B) curves of different hydrogels (HEC, PAH, PAH-OEO, PAH-OEONL).

Note: HEC, hydroxyethyl cellulose; PAH, HEC hydrogel prepared with plasma-activated water; OEO, oregano essential oil; OEONL, oregano essential oil nanoliposomes.

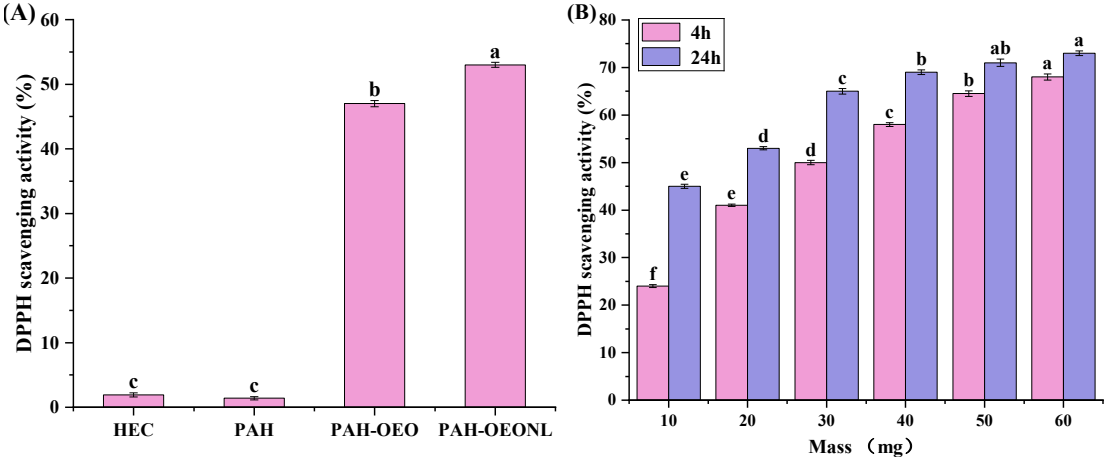
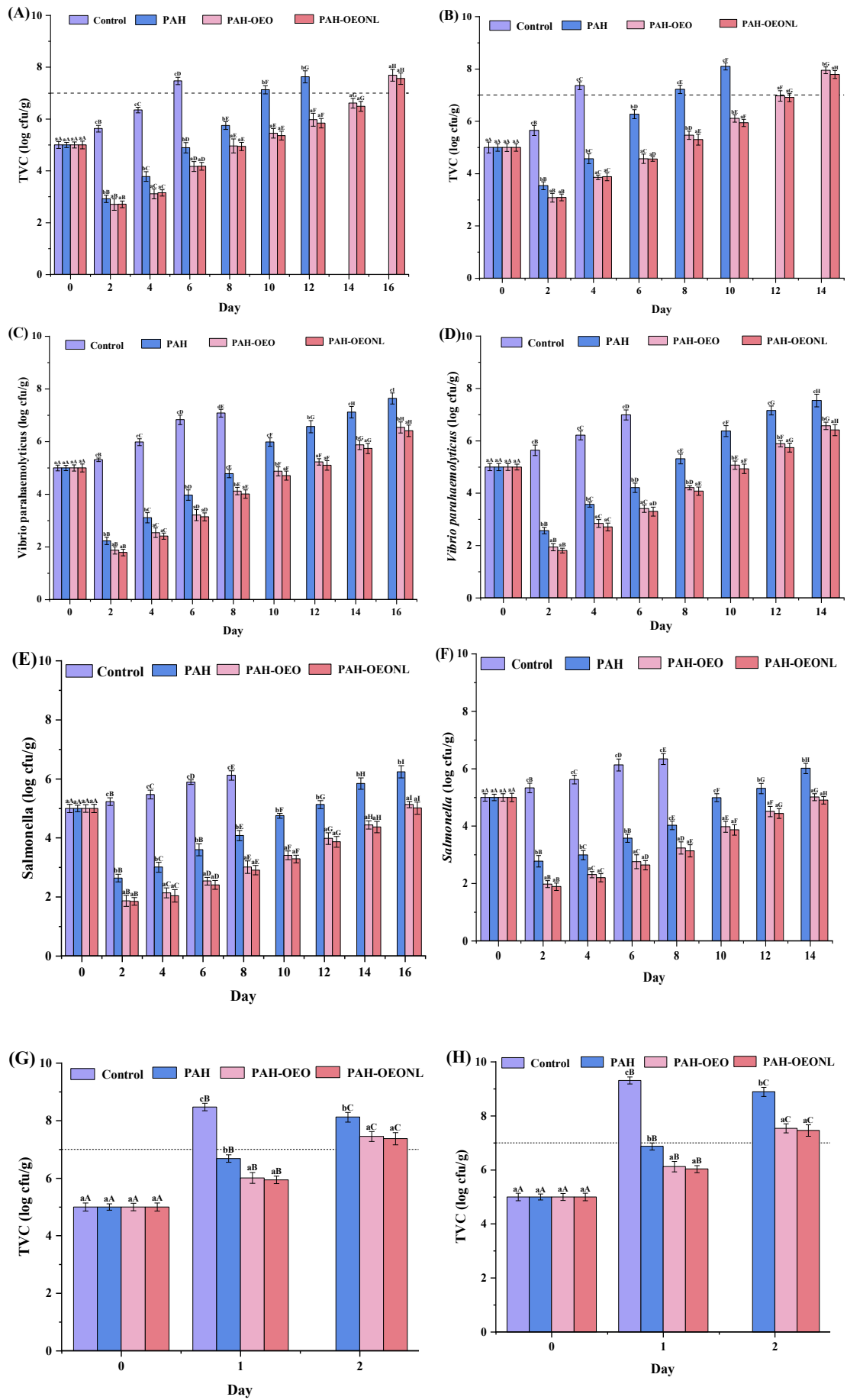


Fig 5 DPPH free radical scavenging activity of different hydrogels (HEC, PAH, PAH-OEO, PAH-OEONL)(A), and PAH-OEONL hydrogel samples with different masses (10–60 mg) after 4 and 24 h of incubation (B).

Note: HEC, hydroxyethyl cellulose; PAH, HEC hydrogel prepared with plasma-activated water; OEO, oregano essential oil; OEONL, oregano essential oil nanoliposomes. Different lowercase letters above the bars indicated significant differences among groups ($p < 0.05$).



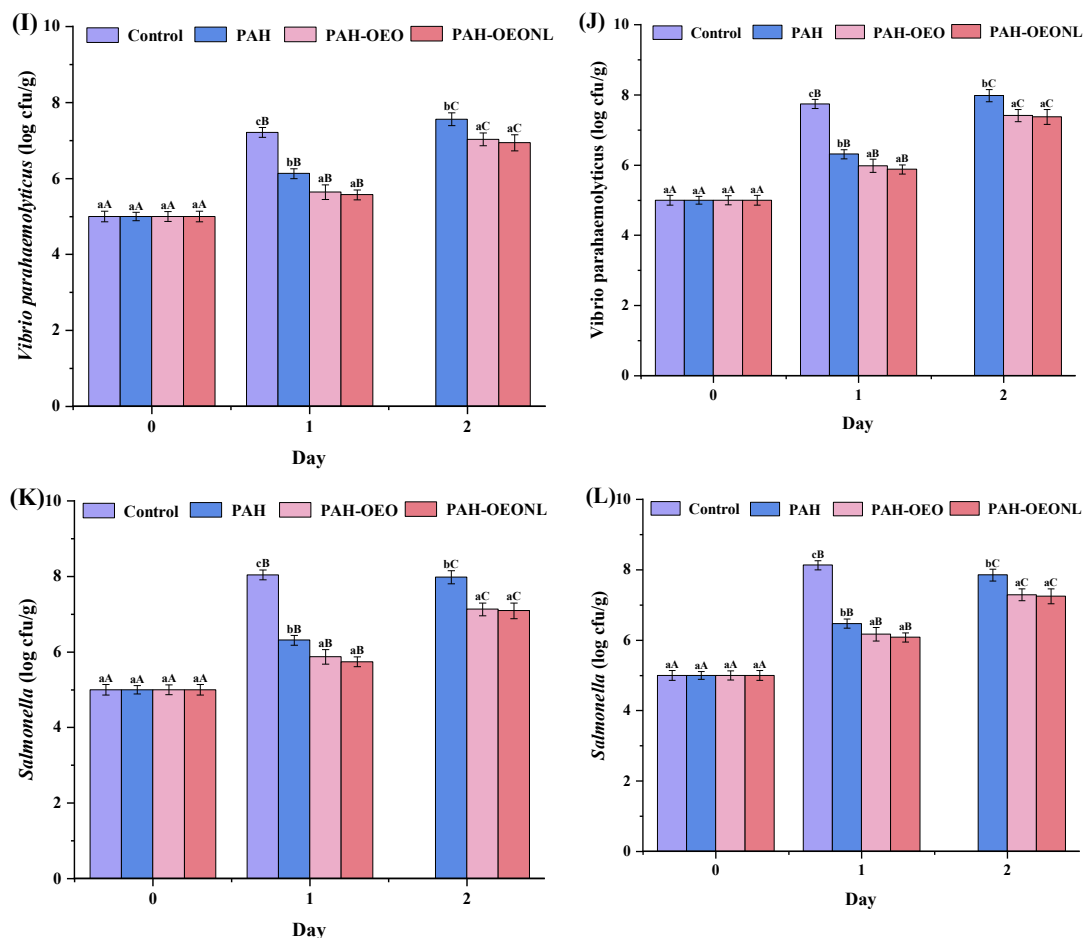


Fig 6 Microbial counts in shrimp meat (A, C, E, G, I, and K) and golden pompano fillets (B, D, F, H, J, and L) under different treatments during storage at 4 °C (A–F) and 25 °C (G–L).

Note: Control, uncoated samples; PAH, HEC hydrogel prepared with plasma-activated water; OEO, Oregano essential oil; OEONL, Oregano essential oil nanoliposomes.

Different uppercase letters indicated significant differences among treatments at the same storage time, while different lowercase letters indicated significant differences during storage within the same treatment group ($p < 0.05$).

Tab 1 Water uptake kinetic models fitting parameters of HEC/PAW hydrogels with different HEC concentrations (2%, 3%, 4%, w/v) at 4 and 25 °C

Sample		First-order kinetic			Peleg			Weibull		
T	Rati	Q _e (%)	k (min ⁻¹)	R ²	k ₁ (min·% ⁻¹)	k ₂ (% ⁻¹)	R ²	Q _e (%)	τ (min)	R ²
4	2%	227.45	0.082	0.9972	0.0124	0.0044	0.9985	227.5	11.32	0.9988
	3%	249.12	0.091	0.9968	0.0108	0.0040	0.9982	249.3	9.86	0.9986
	4%	219.87	0.078	0.9975	0.0131	0.0046	0.9987	220.1	12.15	0.9989
25	2%	282.15	0.125	0.9912	0.0089	0.0035	0.9915	282.3	8.65	0.9958
	3%	294.87	0.138	0.9934	0.0078	0.0033	0.9924	297.0	7.92	0.9967
	4%	271.92	0.119	0.9947	0.0094	0.0037	0.9935	272.1	9.13	0.9981

Notes:
 Q_e: Equilibrium water absorption capacity, (%);
 k: First-order kinetic rate constant, (min⁻¹);
 R²: Coefficient of determination;
 k₁: Peleg rate constant, (min·%⁻¹);
 k₂: Peleg capacity constant, (%⁻¹);
 τ: Characteristic time of Weibull model, (min).

788 **Tab 2** Water holding capacity kinetic models fitting parameters of HEC/PAW hydrogels with
789 different HEC concentrations (2%, 3%, 4%, w/v) at 4 and 25 °C

Sample		Weibull			Exponential decay model			Double exponential model		
T	Rati	W _e (%)	α (d)	R ²	W _e (%)	k (d ⁻¹)	R ²	C (%)	k ₁ (d ⁻¹)	R ²
4	2%	56.82	8.35	0.9996	56.64	0.136	0.992	56.52	0.47	0.9972
	3%	58.84	7.43	0.9991	58.06	0.111	0.993	58.45	0.37	0.9989
	4%	58.13	7.87	0.9993	58.75	0.123	0.999	57.74	0.42	0.9913
25	2%	42.54	0.029	0.9859	42.02	38.55	0.985	42.06	75.1	0.9879
	3%	47.05	0.032	0.9840	46.53	34.23	0.989	46.58	70.4	0.9869
	4%	44.07	0.031	0.9859	43.84	36.04	0.987	43.87	72.0	0.9874

790 **Notes:**

791 W_e: Fitted equilibrium water retention rate, (%);

792 α: Scale parameter related to the characteristic time of the water loss process, (d);

793 R²: Coefficient of determination;

794 k: First-order rate constant describing the overall water loss rate, (d⁻¹);

795 C: Residual or equilibrium water fraction that remains stable at long-term storage, (%);

796 k₁: Rate constant describing rapid water loss at early stages, (d⁻¹).

797 Storage times at 25 °C were converted from hours to days before kinetic fitting.

798

799 **Tab 3** Physicochemical properties of OEONL and antibacterial activity of OEO

OEONL		OEO		
Parameter	Data	Strain	Parameter	Data
EE (%)	79.31 ± 2.86	<i>Vibrio parahaemolyticus</i>	MIC (μL/mL)	0.625
Particle size (nm)	102.31 ± 1.46	<i>Vibrio parahaemolyticus</i>	MBC (μL/mL)	0.625
PDI	0.264 ± 0.014	<i>Salmonella</i>	MIC (μL/mL)	0.625
Zeta potential (mV)	-2.82 ± 0.03	<i>Salmonella</i>	MBC (μL/mL)	1.25

800 **Notes:**

801 OEONL, oregano essential oil nanoliposomes;

802 OEO, oregano essential oil;

803 EE, encapsulation efficiency;

804 PDI, polydispersity index;

805 MIC, minimum inhibitory concentration;

806 MBC, minimum bactericidal concentration.

807 Values of EE, particle size, PDI, and zeta potential were expressed as mean ± SD (n = 3).

808

Tab 4 Thermogravimetric parameters of different hydrogels

Sample	$T_{5\%}$ (°C)	$T_{10\%}$ (°C)	$T_{50\%}$ (°C)	T_{max} (°C)	Maximum mass loss rate (%·°C ⁻¹)	R_{600} (%)
HEC	101.03	162.48	313.28	296.17	-0.528	34.18
PAH	90.40	148.06	309.65	297.33	-0.512	30.97
PAH-OEO	88.62	137.03	306.30	295.33	-0.617	29.31
PAH-OEONL	84.84	137.85	306.79	293.17	-0.880	28.02

Notes:

$T_{5\%}$, $T_{10\%}$, and $T_{50\%}$ represented the temperatures corresponding to 5%, 10%, and 50% weight loss, respectively.

T_{max} represented the temperature at the maximum mass loss rate.

R_{600} represented the residual mass at 600 °C.

The maximum mass loss rate was calculated from the weight–temperature curve as dW/dT , so the unit was expressed as %·°C⁻¹.

Supplementary Files

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- [2026102Supplementaryfigure.docx](#)