

SUPPLEMENTARY INFORMATION

Biodegradable poly(vinyl alcohol) films reinforced with zinc oxide functionalized carbon nanosheets derived from *Punica granatum* peels for sustainable food packaging

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UV-Visible spectrum

As shown in **Figure S1**, the UV–Vis spectra reveal that P-CNs has two distinct absorption peaks. The first one appears around 220 nm, likely due to the $\pi \rightarrow \pi^*$ transition of the C–C bonds. The second peak, a shoulder at approximately 288 nm, corresponds to the $n \rightarrow \pi^*$ transition of the C=O bonds. Upon functionalization with ZnO, noticeable spectral changes occur. A new absorption band appears around 360–380 nm, characteristic of the bandgap absorption of ZnO, confirms the flourishing inclusion of ZnO onto the P-CNs surface. The reduction or disappearance of the shoulder around 280 nm further suggests changes in the oxygen functionalities of P-CNs. These spectral modifications collectively confirm the formation of the ZnO@P-CNs nanocomposite and the effective interaction between ZnO and the P-CNs matrix.

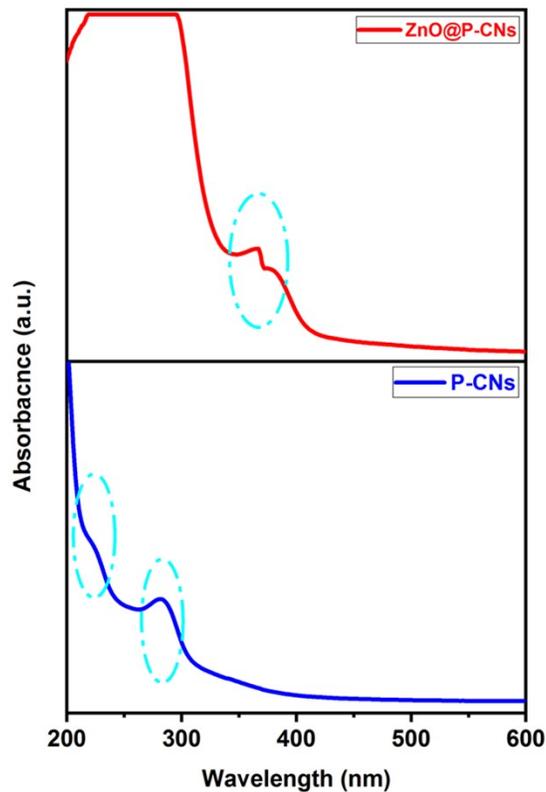


Figure S1. UV-Visible spectrum of P-CNs and ZnO@P-CNs

SEM analysis

The SEM micrograph of P-CNs reveals thin, layered, and sheet-like structures exhibiting a wrinkled or wavy morphology, typical of exfoliated nanosheets. These sheets display a porous and rough surface texture, attributed to the intrinsic characteristics of the biomass precursor and the effects of the carbonization process. The presence of nanoscale folds and crevices observed in the SEM images further confirms the porous, high-surface-area nature of the material an essential feature for applications requiring enhanced surface interactions (**Figure S2a**). The morphology suggests successful oxidation and exfoliation of graphitic carbon derived from the biomass source (pomegranate peel). The EDAX spectrum of P-CNs shows predominant peaks for carbon (C) and oxygen (O), confirming the successful oxidation of carbonaceous material. Additional minor elements like K, Na, Mg or Cl appear from inherent plant minerals in the pomegranate peel. The SEM image of ZnO@P-CNs reveals ZnO uniformly distributed or embedded over the P-CNs. These particles appear as small, spherical or hexagonal clusters, often

anchored on the surface or at the edges of the P-CNs. The ZnO loading slightly increases the roughness and thickness of the sheets, indicating successful interaction between the ZnO and oxygenated functional groups on P-CNs, as confirmed by FTIR earlier. The hybrid morphology suggests good dispersion and interaction between ZnO and P-CNs, which is crucial for antibacterial activity. After ZnO functionalization, the EDAX spectrum clearly shows the appearance of Zn peaks, along with oxygen and carbon. The presence of Zn confirms the successful deposition or anchoring of ZnO on P-CNs (**Figure S2 b**).

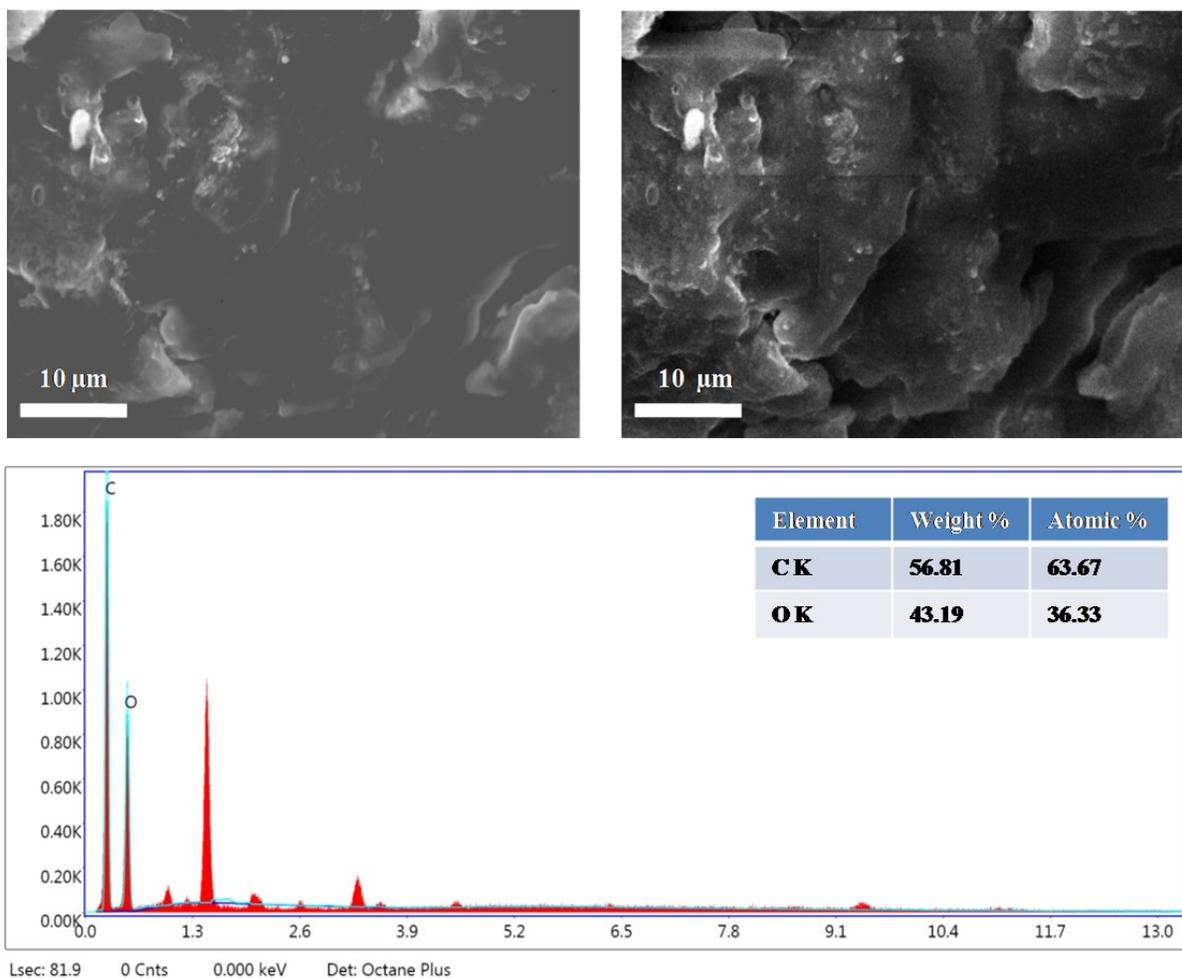


Figure S2 a) SEM-EDAX analysis of P-CNs

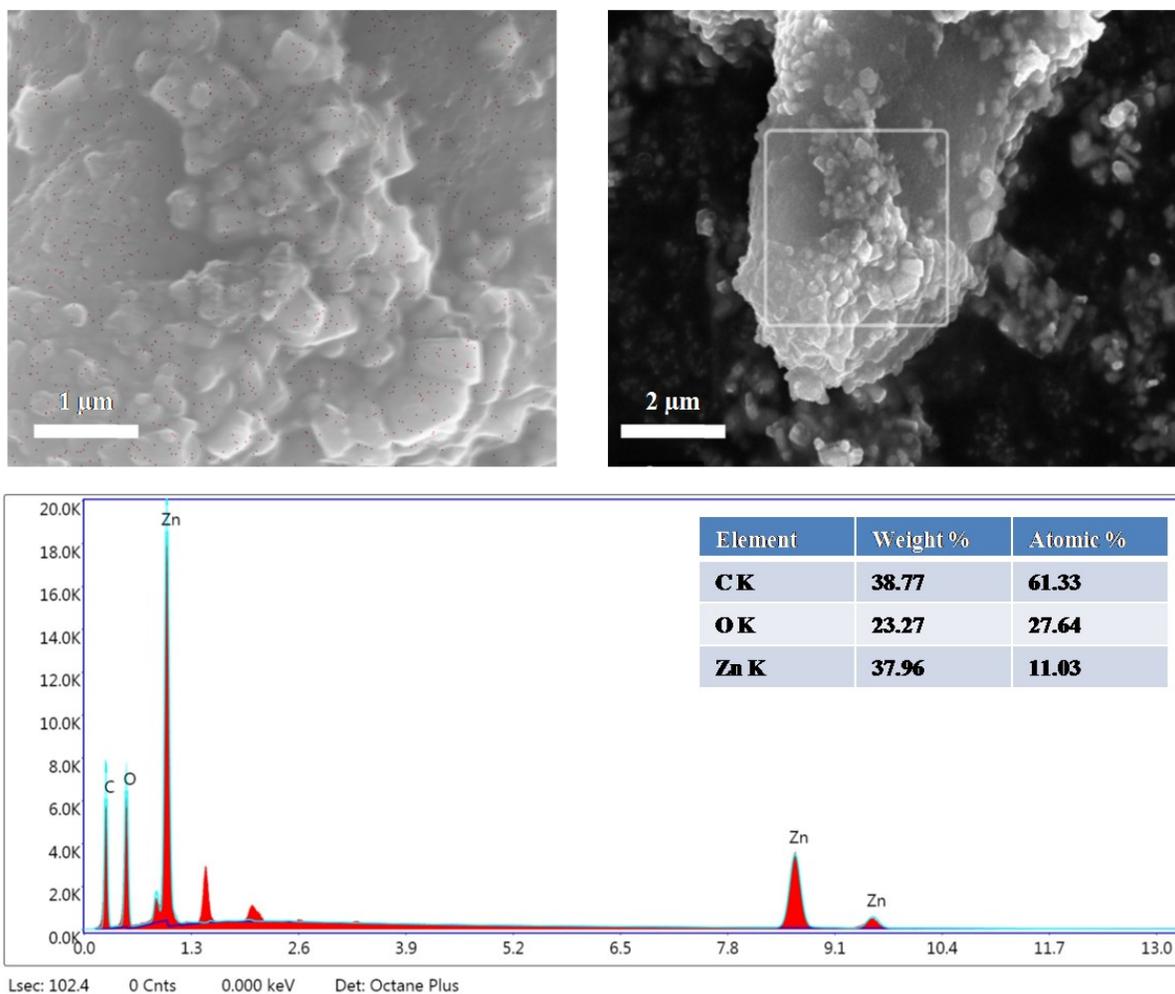


Figure S2 b) SEM-EDAX analysis of ZnO@P-CNs

Antibacterial activity

The antibacterial activity of both P-CNs and ZnO@P-CNs was examined against Gram-positive *S. aureus* and *B. subtilis* bacteria using the agar well diffusion method. However, for gram positive bacteria no clear inhibition zones were observed for these strains under the tested conditions. This may be attributed to the thicker peptidoglycan layer present in Gram-positive bacterial cell walls, which can limit the interaction and penetration of nanomaterials [Figure S3].

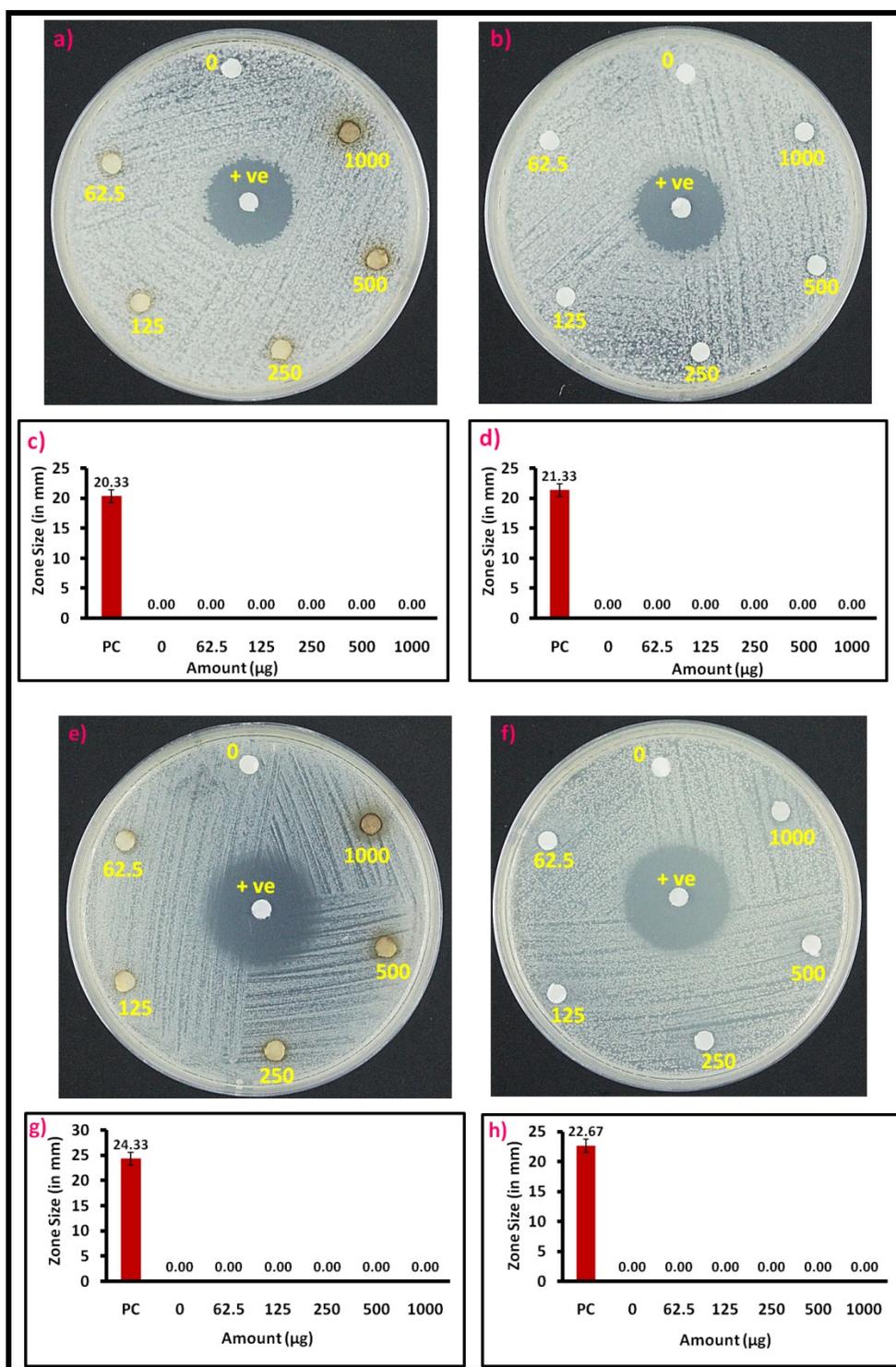


Figure S3. Antibacterial activity of P-CNs and ZnO@P-CNs against a-d) *B. subtilis* and e-h) *S. aureus* treated with ciprofloxacin. Data are mean \pm SD (n=3).