

Article

Electron Beam-Irradiated g-C₃N₄/Ti₃C₂ Nanocomposite Embedded in PVA/SA Hydrogel: An Integrated Platform with Enhanced Photocatalytic Antibacterial Activity

Rui Feng [†], Xuguang Chen [†], Yue Wu, Kaidi Xu, Yu Zhao, Jiale Lu, Zenghui Shi, Huangqin Chen ^{*} and Bin Huang ^{*}

School of Stomatology and Ophthalmology, Hubei University of Science and Technology, Xianning 437000, China; fengrui066@163.com (R.F.); cxg15098096179@outlook.com (X.C.); wuxiaoxiao5@outlook.com (Y.W.); kaidixu04@163.com (K.X.); 15907241425@139.com (Y.Z.); lujial2026@outlook.com (J.L.); shizenghui2005723@outlook.com (Z.S.)

^{*} Correspondence: chenhuangqin79@163.com (H.C.); huangbin914@163.com (B.H.)

[†] These authors contributed equally to this work.

Abstract

Photodynamic antibacterial therapy presents a promising strategy for combating bacterial infections due to its non-invasive nature and low potential for inducing resistance. In this work, we developed a series of electron beam-modified graphitic carbon nitride (g-C₃N₄, CN) and titanium carbide (Ti₃C₂, TC) nanocomposites, which were subsequently incorporated into polyvinyl alcohol/sodium alginate (PVA/SA) hydrogels through physical cross-linking. The optimized 200CN/1TC composite hydrogel (where 200CN denotes 200 kGy irradiation dose, and 1TC represents 1 wt% TC content) maintained excellent biocompatibility with cell viability exceeding 80% even at the highest nanomaterial loading (8% 200CN/1TC). Notably, the 8% 200CN/1TC composite hydrogel displayed substantial antibacterial activity, forming inhibition zones of 12.3 mm and 10.8 mm against *Staphylococcus aureus* and *Escherichia coli*, respectively. The improved performance may be explained by the combined effects of enhanced electron transfer between the component materials and the unique two-dimensional structure of the nanocomposites, though further investigation is required to fully elucidate the underlying mechanisms. This study provides a feasible approach for developing efficient antibacterial hydrogel systems and offers valuable perspectives on the design of nanomaterial-based biomedical materials for wound healing and infection control applications.

Keywords: g-C₃N₄; Ti₃C₂ MXene; electron beam irradiation; antibacterial hydrogel; photocatalytic activity



Academic Editors: Shima Momen and Mahsa Majzoobi

Received: 4 January 2026

Revised: 5 February 2026

Accepted: 11 February 2026

Published: 14 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Among the myriad challenges confronting human health, bacterial infections remain a persistent and evolving threat, significantly impacting global public health security. Their intricate and mutable nature, coupled with increasingly sophisticated transmission mechanisms, poses a severe challenge to the quality of human life [1–3]. The advent of antibiotics marks a pivotal milestone in medical history, effectively containing the spread of bacterial infections and saving countless lives by disrupting bacterial cell wall synthesis, compromising cell membranes, or inhibiting genetic material replication. However, the widespread and even abusive use of antibiotics has led to the emergence and escalation of bacterial resistance [4–6]. The relentless evolution and dissemination of resistant strains

including enzymatic drug inactivation, efflux pump overexpression, and target site modification, have progressively eroded the efficacy of conventional antibiotics and posed unprecedented challenges to the medical community. The World Health Organization has identified antimicrobial resistance (AMR) as one of the top ten global public health threats, with mortality attributable to AMR projected to rise dramatically in the coming decades if effective countermeasures are not implemented. Given that the pipeline for new antibiotics cannot keep pace with the relentless evolution of resistance mechanisms, creating an urgent and critical need for novel, efficient antibacterial strategies that can circumvent existing resistance pathways.

In this context, nanotechnology and materials science have opened new frontiers for combating bacterial infections. Among various innovative platforms, two-dimensional (2D) materials have garnered significant research interest due to their unique physicochemical properties arising from their ultra-thin, planar structures and high specific surface areas [7–9]. Graphitic carbon nitride (g-C₃N₄, CN), a metal-free polymeric semiconductor, has emerged as a particularly promising candidate in antibacterial material research. Its appealing attributes include a moderate bandgap ($E_g = 2.7$ eV) enabling visible-light activation, exceptional physicochemical and thermal stability, low toxicity, ease of synthesis from abundant precursors, and high specific surface area [10–14]. These properties underpin its application in photocatalysis, where upon light irradiation, it generates reactive oxygen species (ROS) such as $\bullet\text{O}_2^-$ and $\bullet\text{OH}$, which can induce oxidative stress and irreversibly damage bacterial cellular components [15]. Despite these advantages, the practical application of pristine CN is often hampered by the rapid recombination of photogenerated electron-hole pairs, which limits its quantum efficiency and overall photocatalytic performance. To overcome this limitation, various modification strategies have been explored, including elemental doping, heterojunction construction with other semiconductors, and surface functionalization [16]. In an innovative approach, this study introduces electron beam irradiation (EBI) technology as a potent tool for enhancing the photocatalytic activity of CN. The high-energy electrons from EBI interact with the CN structure, inducing defects, creating active sites, and potentially modifying its electronic structure through ionization and excitation effects. These modifications are anticipated to improve charge carrier separation and enhance light absorption, thereby boosting its ROS-generating capability for antibacterial applications.

Simultaneously, another family of 2D materials, MXenes—particularly Ti₃C₂T_x (TC) derived from the etching of MAX phases—have attracted considerable attention for their exceptional metallic conductivity, hydrophilic surfaces, and tunable terminal functional groups (-O, -OH, -F) [17–21]. These properties endow TC with high specific surface area, excellent electrochemical activity, and good biocompatibility, making it suitable for applications ranging from energy storage to biomedicine [22]. When combined with CN, TC can act as an efficient electron sink due to its superior electrical conductivity. The formation of a heterojunction interface facilitates the swift transfer of photogenerated electrons from CN to TC, effectively suppressing charge recombination and synergistically enhancing the overall photocatalytic efficiency of the composite material [23,24]. Furthermore, the sharp edges of MXene nanosheets can contribute to physical piercing of bacterial membranes, adding a complementary mechanical mechanism to the predominant photocatalytic antibacterial action [25–27].

For practical biomedical, integrating nano-photocatalysts into a suitable carrier matrix is crucial to ensure localized delivery, facilitate recovery, and enhance biocompatibility. Hydrogels, three-dimensional hydrophilic polymer networks capable of imbibing large amounts of water, represent an ideal platform for this purpose. Their tunable physicochemical properties, high water content mimicking natural tissues, excellent biocompatibility,

and ability to act as reservoirs for active compounds make them highly attractive for wound dressing and drug delivery applications [28–30]. In particular, antibacterial hydrogels can be engineered to disrupt bacterial membranes or release antibacterial agents in a controlled manner, thereby mitigating the risk of resistance development associated with systemic antibiotic administration [31,32]. Photosensitive antibacterial hydrogels, which generate lethal ROS upon light irradiation, offer a spatially and temporally controllable antimicrobial strategy that does not induce resistance [33,34]. Polyvinyl alcohol (PVA) and sodium alginate (SA)—both biodegradable and non-toxic polymers—are widely used to form stable hydrogels via physical crosslinking methods such as freeze-thaw cycling, providing a biocompatible environment for the incorporation of photoactive nanomaterials.

Therefore, building upon preliminary optimization, this study selected electron beam-irradiated CN (processed at 200 kGy, denoted as 200CN) and combined it with 1 wt% TC to construct 200CN/1TC nanocomposites. These composites were uniformly dispersed into a PVA/SA hydrogel matrix, and a series of composite hydrogels with varying nanomaterial loadings were fabricated through repeated freeze-thaw cycles. A comprehensive suite of characterization techniques was employed to meticulously analyze the resulting materials: Fourier-transform infrared spectroscopy (FT-IR) probed chemical bonding and functional groups; X-ray diffraction (XRD) elucidated crystalline structure; ultraviolet-visible diffuse reflectance spectroscopy (UV-Vis DRS) assessed optical absorption properties; and nitrogen adsorption-desorption analysis (BET) determined specific surface area and pore texture. Thermogravimetric analysis (TGA) evaluated thermal stability, while cytotoxicity assays (e.g., MTT) on L929 fibroblasts assessed biocompatibility. Finally, the antibacterial efficacy was quantitatively evaluated against model Gram-negative (*Escherichia coli*, *E. coli*) and Gram-positive (*Staphylococcus aureus*, *S. aureus*) bacteria using the agar diffusion method.

By integrating the superior photocatalytic properties of electron beam-modified CN/TC with the biocompatible and versatile PVA/SA hydrogel platform, this study aims to develop a novel, efficient, and safe photoresponsive antibacterial system. This approach seeks to transcend the limitations of conventional antibacterial modalities and offer a promising alternative strategy for managing bacterial infections, particularly in topical applications such as wound care. We anticipate that the convergence of advanced material design with biomedical engineering will open new pathways for addressing the critical challenge of antimicrobial resistance.

2. Results and Discussion

2.1. Chemical Structure and Interactions in Nanomaterials and Composite Hydrogels

FT-IR spectroscopy was employed to analyze the functional group composition and chemical interactions within the prepared nanomaterials (TC, CN) and the hydrogel matrices (PVA/SA and the 8% CN/TC composite hydrogel, 8% g-TC). The spectra, presented in Figure 1, provide critical insights into the molecular structure and interfacial bonding.

The spectrum of TC displays characteristic absorption peaks at 3410 cm^{-1} , 1614 cm^{-1} , 1406 cm^{-1} , 1080 cm^{-1} , and 542 cm^{-1} . The broad band centered at 3410 cm^{-1} is indicative of O-H stretching vibrations, originating from adsorbed water molecules or surface hydroxyl (-OH) groups. The peak at 1614 cm^{-1} corresponds to the C=O stretching vibration, suggesting surface oxidation. The absorptions at 1406 cm^{-1} and 1080 cm^{-1} are attributable to C-F (from the etching process) and C-O stretching vibrations, respectively, while the peak at 542 cm^{-1} confirms the presence of Ti-O bonds. This combination of hydrophilic functional groups (-OH, C=O) is crucial as it enhances the dispersibility of TC nanosheets in aqueous media, facilitating their uniform distribution within the hydrogel network and promoting stronger interfacial adhesion with the polymer matrix.

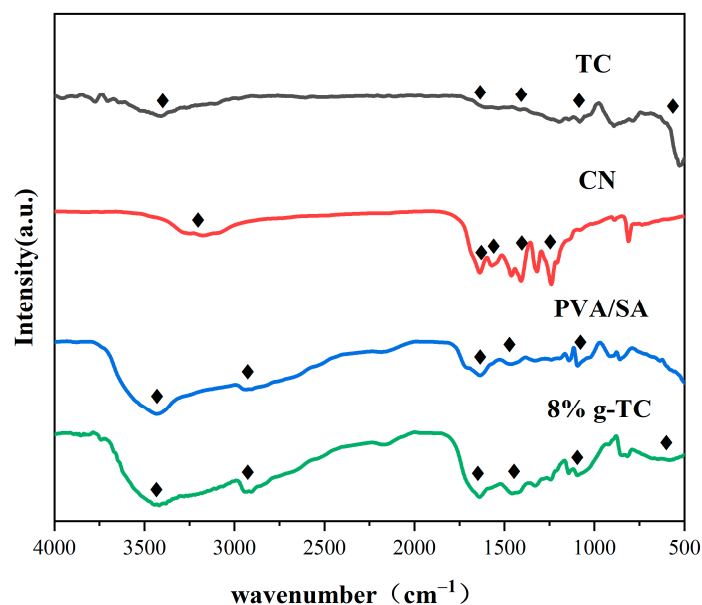


Figure 1. FT-IR spectrum of the prepared nanomaterials and the hydrogel.

For CN, the FT-IR spectrum exhibits the characteristic vibrational modes of its heptazine (tri-s-triazine) heterocyclic skeleton. The broad absorption band centered around 3218 cm^{-1} is typically assigned to the stretching vibrations of terminal N-H groups and/or O-H groups from adsorbed water molecules. More accurately, the defining spectral features are found in the $1200\text{--}1650\text{ cm}^{-1}$ region, which serves as the fingerprint for the CN matrix. The distinct set of absorption bands in this region are attributed to the stretching vibrations of the aromatic CN heterocycles: the peaks at approximately 1645 cm^{-1} and 1568 cm^{-1} are associated with the C=N and C-N stretching vibrations, respectively. Meanwhile, the series of strong bands between 1230 cm^{-1} and 1460 cm^{-1} correspond to the bridging C-N-C units or aromatic C-N stretching vibrations within the continuous heptazine framework.

The FT-IR spectrum of the pure PVA/SA hydrogel shows the expected features of its constituents. The broad and intense absorption peak observed at approximately 3420 cm^{-1} is characteristic of the stretching vibration of hydroxyl groups (O-H), primarily originating from the extensive hydrogen-bonding network present in both PVA and SA. A distinct band at 2935 cm^{-1} corresponds to the symmetric and asymmetric C-H stretching vibrations of the polymer backbones. The presence of sodium alginate is unambiguously confirmed by two key features: a strong band at 1635 cm^{-1} , assigned to the asymmetric stretching vibration of the carboxylate anion (-COO^-), and another at 1465 cm^{-1} , attributed to its symmetric stretching vibration. Furthermore, a prominent peak at 1082 cm^{-1} is identified as the C-O stretching vibration, characteristic of the alcoholic groups in PVA. The concurrent presence of these distinctive alginate and PVA absorptions verifies the successful formation of the composite hydrogel, wherein the carboxylate groups are vital for forming the polyelectrolyte complex that stabilizes the entire hydrogel network.

The FT-IR spectrum of the 8% g-TC composite hydrogel provides definitive evidence for the successful integration of all components and reveals substantial molecular-level interactions within the hybrid material. A primary observation is the shift of the hydroxyl (O-H) stretching vibration to a lower wavenumber of 3430 cm^{-1} , accompanied by noticeable peak broadening. This phenomenon is directly attributed to the formation of extensive hydrogen bonding between the hydroxyl groups of the PVA/SA matrix and the functional groups present on the surfaces of both CN and TC. The spectrum conclusively confirms the presence of CN through its characteristic vibrational modes. The distinct absorption bands observed at 1573 cm^{-1} and 1637 cm^{-1} are assigned to the stretching vibrations of

C≡N bonds. Furthermore, a series of four bands at 1240 cm^{-1} , 1317 cm^{-1} , 1403 cm^{-1} , and 1460 cm^{-1} are identified as the stretching vibrations of aromatic C-N bonds within the heptazine (s-triazine) ring structure. The characteristic breathing vibrational mode of the s-triazine ring is also clearly visible at 855 cm^{-1} . A broad absorption envelope spanning the $3000\text{--}3400\text{ cm}^{-1}$ region can be ascribed to the overlapping contributions from the stretching vibrations of residual terminal amino groups ($-\text{NH}_2/-\text{NH}$) in the CN and O-H groups from adsorbed water. Simultaneously, the signature of TC is distinctly identifiable. The characteristic peak corresponding to the C=O stretching vibration is observed at 1639 cm^{-1} , while the Ti-O stretching vibration appears at 573 cm^{-1} . The persistence of all characteristic peaks from CN and TC in the composite spectrum, albeit with minor positional shifts compared to their pristine states, confirms that the nanomaterials have been successfully incorporated into the hydrogel network without significant chemical degradation. More importantly, these subtle peak shifts collectively underscore the existence of multifaceted physicochemical interactions—including hydrogen bonding and van der Waals forces—among PVA, SA, CN, and TC. These interactions are fundamental to the structural integrity and performance of the resulting hybrid hydrogel.

2.2. Crystalline Structure and Exfoliation Behavior of Nanomaterials and Composite Hydrogels

XRD analysis was conducted to investigate the crystalline phases and structural changes in the components and the final composite hydrogel (Figure 2).

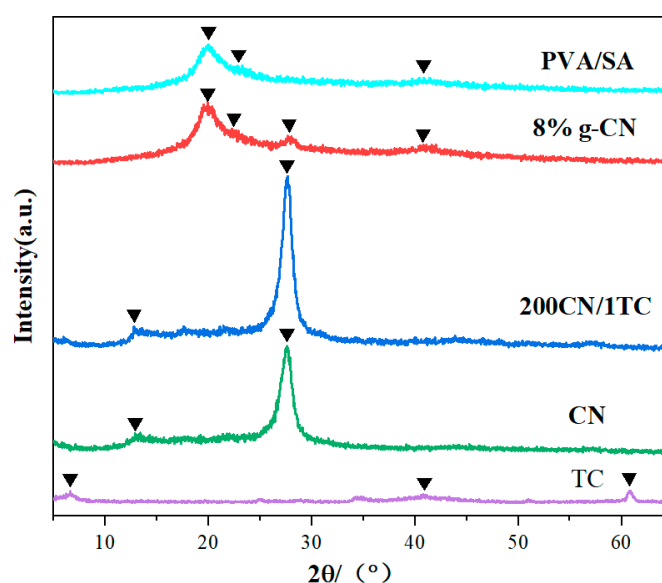


Figure 2. XRD analysis of 200CN/1TC, 8% g-TC and PVA/SA.

The XRD pattern of TC shows a weak, broad (002) peak at around $2\theta = 6.6^\circ$, which is typical for layered MXenes after delamination, indicating an expanded interlayer spacing. The weaker peaks at higher angles (e.g., 40.9° , 60.9°) correspond to (105) and (110) planes, confirming the preservation of the MXene crystal structure post-etching. For CN, two characteristic peaks are observed: a weak (100) peak at 13.2° , related to in-plane structural packing of tri-s-triazine units, and a strong (002) peak at 27.5° , corresponding to the interlayer stacking of the conjugated aromatic systems with a d-spacing of approximately 0.32 nm. The intensity of the (002) peak is a marker of the degree of graphitization, which influences electronic conductivity and photocatalytic efficiency.

The pattern of the 200CN/1TC nanocomposite shows the dominant (002) peak of CN at 27.5° with increased intensity and slight sharpening compared to pristine CN. This enhancement in crystallinity can be attributed to the electron beam irradiation treatment,

which potentially removes amorphous carbonaceous residues and promotes structural ordering, leading to improved charge carrier mobility. The characteristic peaks of TC are not distinctly visible in the composite, likely due to its low relative concentration (1 wt%), high dispersion, and the overlapping of its main (002) peak with the broad background.

The XRD pattern of the PVA/SA hydrogel exhibits a semi-crystalline nature, with a strong diffraction peak at 19.8° , a shoulder at 22.9° and a weak peak at 40.6° , assigned to the (101), (200) and (102) planes of crystalline PVA, respectively. The presence of these peaks indicates that the freeze-thaw cycling successfully induced crystallite formation within the PVA matrix, which acts as physical cross-links, contributing to the hydrogel's mechanical strength.

In the pattern of the 8% g-TC composite hydrogel, the PVA peaks remain prominent. However, the intensity of the characteristic CN (002) peak at 27.5° is significantly reduced and broadened. This attenuation is a classic signature of successful exfoliation and dispersion of the CN nanosheets within the polymer matrix. The polymer chains intercalate between the CN layers, disrupting the long-range stacking order and leading to a loss of peak intensity. The slight shift of the PVA shoulder peak to a lower angle (22.6°) further suggests an increase in the d-spacing of the PVA crystallites, possibly due to the interaction with the nanofillers. These observations collectively confirm the successful fabrication of a nanocomposite hydrogel where the 2D nanomaterials are well-integrated into the polymeric network.

2.3. Optical Absorption and Band Gap Modulation via 200CN/1TC Nanocomposite Incorporation in PVA/SA Hydrogels

The optical properties of the hydrogels were evaluated using UV-Vis DRS, and the corresponding Tauc plots were used to determine the band gap energy (E_g), as shown in Figure 3. The pure PVA/SA hydrogel exhibits a wide band gap of 3.01 eV, which is typical for insulating polymers and implies limited light absorption in the visible region. In stark contrast, the 8% g-TC composite hydrogel shows a significantly reduced band gap of 2.80 eV. This narrowing of the band gap is a direct consequence of incorporating the narrow-bandgap semiconductor CN ($E_g \approx 2.7$ eV) and the metallic TC. The presence of TC, with its high electrical conductivity, can introduce states within the band gap of CN and facilitate a Schottky junction at the interface, effectively lowering the energy required for electron excitation. This enhanced visible-light absorption is paramount for the hydrogel's application as a photoactive antibacterial material, as it allows for the utilization of a broader spectrum of ambient light to generate ROS.

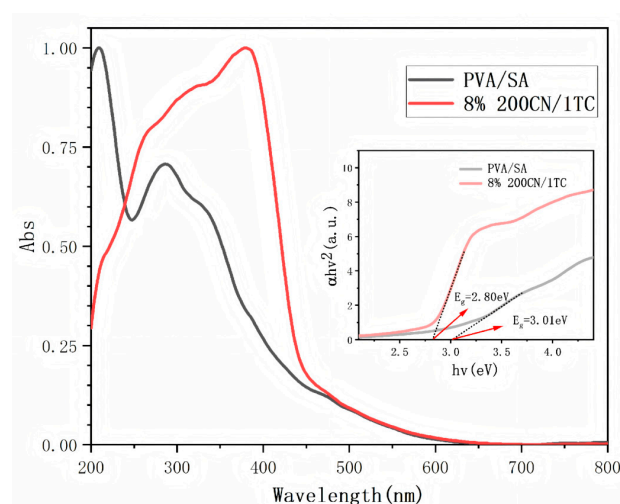


Figure 3. UV-Vis Analysis of PVA/SA and 8% g-TC.

2.4. Pore Structure and Specific Surface Area Enhancement in 200CN/1TC-Loaded PVA/SA Composite Hydrogels

The porous texture of the hydrogels was quantitatively analyzed using N₂ adsorption-desorption isotherms (Figure 4), with data summarized in Table 1.

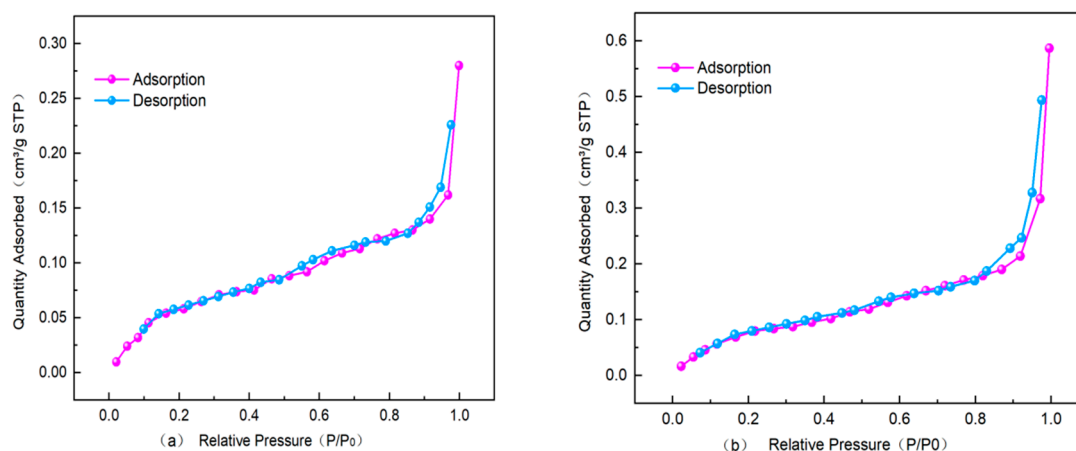


Figure 4. N₂ adsorption-desorption isotherms of PVA/SA (a) and 8% g-TC (b) hydrogels.

Table 1. BET analysis of PVA/SA and 8% g-TC hydrogels.

Sample	BET Specific Surface Area [m ² g ^{−1}]	Total Pore Volume [cm ³ g ^{−1}]	Micropore Volume [cm ³ g ^{−1}]
PVA/SA	0.2279	0.00038257	0.00010732
8% g-TC	0.35889	0.00081308	0.00013758

The isotherms for both the PVA/SA and 8% g-TC hydrogels can be classified as Type IV with H4-type hysteresis loops according to International Union of Pure and Applied Chemistry guidelines. This combination is characteristic of microporous and mesoporous materials, specifically those containing narrow slit-shaped pores. In such systems, mesopores primarily serve as transport channels for mass transfer, while the smaller micropores function similarly to molecular sieves, enabling selective screening and separation of molecular species. For the 8% g-TC composite hydrogel, the incorporated CN and TC nanosheets interact closely with the polymer matrix, effectively modifying the mesoporous surface and creating additional interfaces. This nanomaterial-hydrogel interaction contributes to the enhanced specific surface area and improved adsorption performance observed in the composite material, demonstrating the successful integration of nanofillers within the porous hydrogel architecture.

The specific surface area (SSA) of the PVA/SA hydrogel was calculated to be 0.2279 m²/g. Upon incorporation of 8% 200CN/1TC, the SSA increased to 0.3589 m²/g, representing a significant enhancement of over 57%. This substantial increase can be directly attributed to two factors: first, the intrinsic high surface area of the 2D nanomaterials (CN and TC) themselves; second, and more importantly, the role of these nanofillers in creating a finer and more intricate pore structure within the hydrogel matrix. The nanomaterials disrupt the formation of large ice crystals during freezing, leading to smaller pores upon thawing, which consequently increases the total surface area. A higher surface area provides more active sites for potential interactions with bacterial cells or for the diffusion of reactive oxygen species, thereby potentially enhancing the antibacterial efficacy of the composite hydrogel.

2.5. Structural Characterization of the PVA/SA and 8% g-TC Composite Hydrogels

The surface and cross-sectional morphologies of the PVA/SA and 8% g-TC composite hydrogels were examined by SEM (Figure 5). As shown in Figure 5a,b the surface of the pure PVA/SA hydrogel appeared smooth and dense, whereas the incorporation of 200CN/1TC nanocomposite resulted in a more textured surface with a fibrous or strip-like topography. Despite this morphological alteration, the composite hydrogel remained uniformly dense, indicating that the nanofillers were well integrated into the polymer matrix without inducing macro-scale defects.

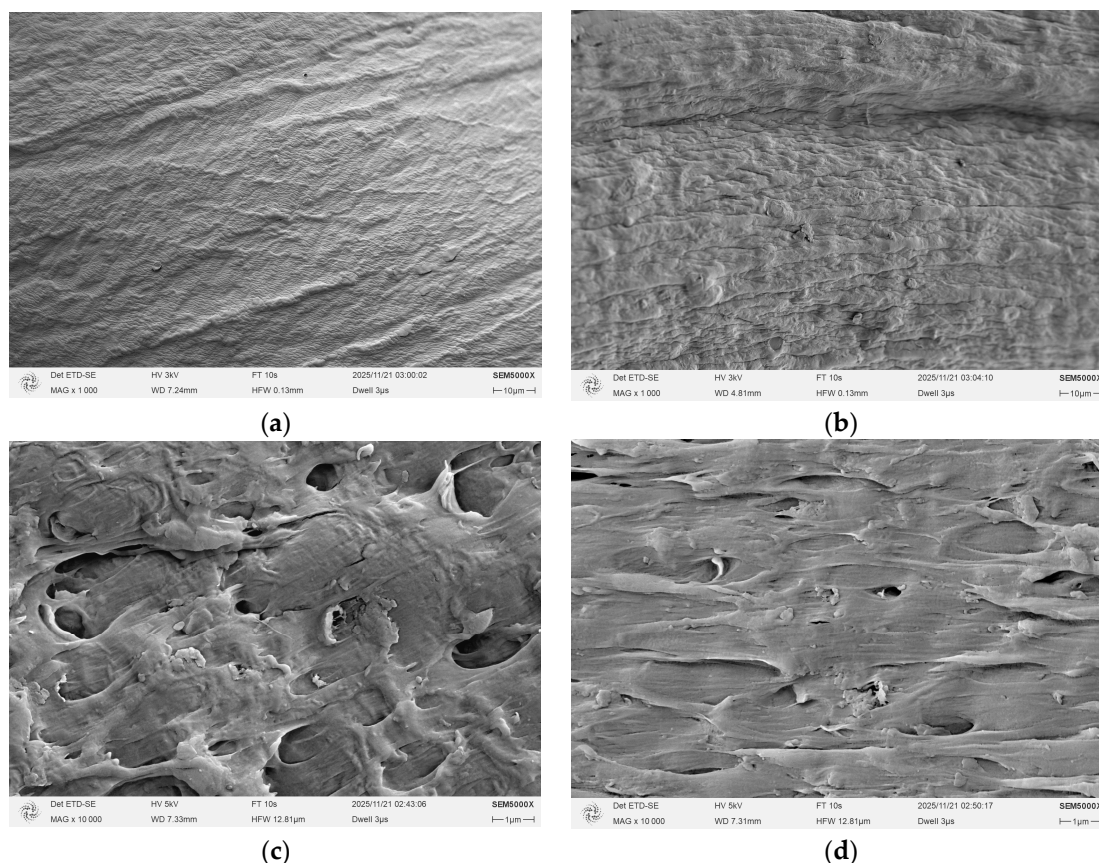


Figure 5. The surface (a,b) and cross-sectional (c,d) morphology of PVA/SA and 8% g-TC hydrogels.

From the cross-sectional views (Figure 5c,d), the pure PVA/SA hydrogel exhibited a highly porous internal structure, which is characteristic of freeze-thaw crosslinked hydrogels. In contrast, the 8% g-TC composite hydrogel showed a moderate reduction in pore number and a more compact internal architecture, suggesting that the embedded nano-materials could serve as additional crosslinking points or nucleation sites during gelation, thereby slightly refining the pore structure while maintaining overall interconnectivity.

2.6. Thermal, Mechanical, and Swelling Properties of 200CN/1TC-Reinforced PVA/SA Composite Hydrogels

The thermal stability and decomposition behavior of the 8% g-TC composite hydrogel were investigated by TGA, with the thermogram presented in Figure 6. The experimental data unequivocally demonstrated the exceptional thermal stability of the 8% g-TC composite hydrogel, primarily attributed to the robust crosslinking structure formed between SA and PVA. This dense intermolecular network effectively hinders the chain mobility and volatilization of degradation products, thereby delaying the thermal decomposition process and improving the overall structural integrity of the hydrogel. The TGA curve reveals

a multi-stage decomposition process, reflecting the complex composition of the material. The initial minor mass loss (7.96%) below 190 °C is associated with the evaporation of physically adsorbed and bound water. The strong cross-linked network, reinforced by the nanomaterials, effectively retains water, as indicated by this gradual initial loss. The second, most significant mass loss step occurs between 190 °C and 360 °C. This stage is primarily due to the thermal degradation of the polymer backbone, including the dehydration of PVA chains, decarboxylation of sodium alginate, and the breakdown of the glycosidic linkages in SA. During this stage, complex intramolecular and intermolecular rearrangement reactions gradually formed highly organized and thermally stable biochars, resulting in a weight loss rate of approximately 66.21% for the 8% g-TC composite hydrogel. The third stage (360 °C to 628 °C) involves further pyrolysis of the carbonaceous residue formed in the previous stage. Finally, above 628 °C, slow continued weight loss occurs due to the oxidation of the remaining char.

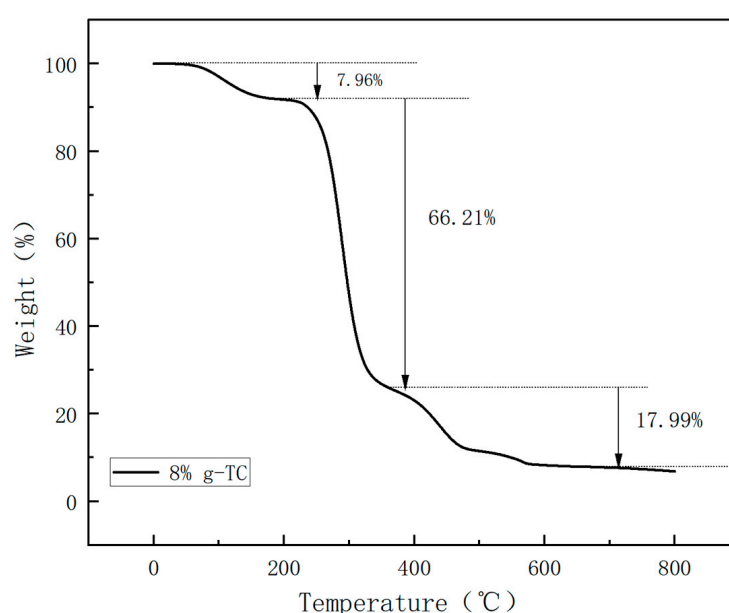


Figure 6. Thermogravimetric analysis (TGA) curve of the 8% 200CN/1TC composite hydrogel (8% g-TC).

The mechanical performance of the hydrogels was assessed through tensile testing. Pure PVA/SA hydrogels exhibited a tensile strength of approximately 1.2 ± 0.2 MPa and an elongation at break of around $180 \pm 15\%$. Upon incorporation of the 200CN/1TC nanocomposite, the mechanical properties showed a clear concentration-dependent trend. With increasing nanomaterial loading, the tensile strength gradually improved, reaching a maximum of 2.1 ± 0.3 MPa for the 8% 200CN/1TC composite hydrogel. This enhancement can be attributed to the reinforcing effect of the well-dispersed CN and TC nanosheets, which act as nanofillers and potentially facilitate additional physical crosslinking within the polymer network. In contrast, the elongation at break displayed a moderate decrease as the nanomaterial content increased, with the 8% composite hydrogel showing an elongation of approximately $120 \pm 10\%$. This reduction suggests that the embedded nanomaterials slightly restrict polymer chain mobility, leading to a less ductile but mechanically stronger network.

The swelling behavior of the hydrogels was evaluated and pure PVA/SA hydrogels exhibited an equilibrium swelling ratio of approximately $280 \pm 15\%$. Incorporation of the 200CN/1TC nanocomposite led to a concentration-dependent decrease in swelling capacity. As the nanomaterial loading increased from 0% to 8%, the equilibrium swelling

ratio gradually reduced from $280 \pm 15\%$ to $210 \pm 12\%$ for the 8% composite hydrogel. This trend can be attributed to the nanosheets occupying pore space and restricting water penetration, enhanced physical interactions between nanofillers and the polymer network tightening the matrix, and the introduction of less hydrophilic interfacial regions. Despite the decrease, all composite hydrogels maintained considerable swelling capacity ($>200\%$), suitable for wound dressing applications where controlled fluid absorption and retention are required. These results demonstrate that the swelling properties of PVA/SA hydrogels can be effectively modulated through the incorporation of 200CN/1TC nanocomposites.

2.7. In Vitro Cytocompatibility of 200CN/1TC-PVA/SA Composite Hydrogels

In this study, the MTT assay was employed to evaluate the effects of PVA/SA hydrogels containing 200CN/TC at concentrations of 0%, 2%, 4%, and 8% on the viability of L929 fibroblasts under light and dark conditions. The results (Figure 7) indicated that in the dark, no significant reduction in cell viability was observed across all tested concentrations. Under light exposure, a concentration-dependent decrease in cell viability was noted; however, even at the highest concentration of 8% 200CN/TC, cell viability remained above 80%. These findings suggest that the hydrogel exhibits no apparent cytotoxicity in the absence of light, and while light activation moderately influences cellular activity, the material maintains favorable biocompatibility under both experimental conditions.

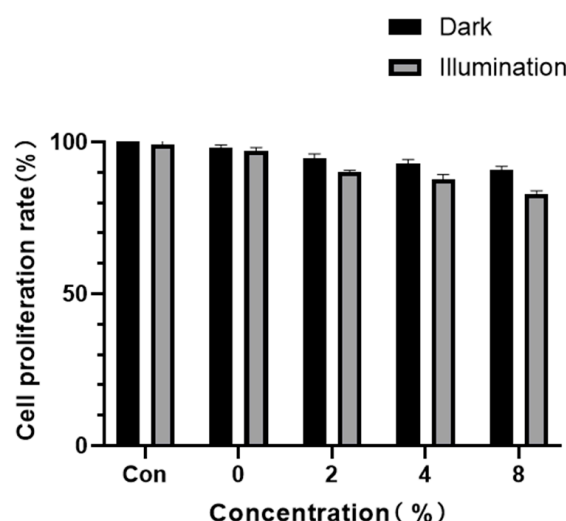


Figure 7. Cell viability of composite hydrogels.

2.8. Light-Induced Intracellular ROS Generation

The intracellular ROS levels in L929 fibroblasts treated with extracts of the composite hydrogels were assessed under both dark and light conditions (670 nm laser irradiation, 0.45 W/cm^2 , 10 min). As shown in Figure 8, under dark conditions, all groups showed minimal green fluorescence, indicating baseline ROS levels regardless of the 200CN/1TC loading. In contrast, under light irradiation, a significant concentration-dependent enhancement of fluorescence intensity was observed with increasing nanocomposite content (0%, 2%, 4%, and 8%). The 8% 200CN/1TC group exhibited the strongest fluorescence signal, confirming the highest light-triggered ROS production. These results clearly demonstrate that the composite hydrogel promotes intracellular ROS generation in a light-activated and concentration-dependent manner, reinforcing its photodynamic antibacterial mechanism.

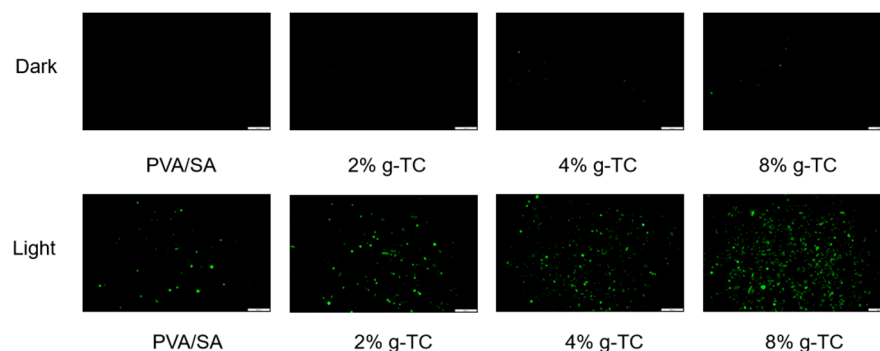


Figure 8. Intracellular ROS generation in L929 fibroblasts treated with composite hydrogel extracts under dark and light conditions (DCFH-DA assay).

2.9. Antibacterial Activity of 200CN/1TC-PVA/SA Composite Hydrogel

The antibacterial performance of the composite hydrogels was assessed against Gram-negative *E. coli* and Gram-positive *S. aureus* using the agar diffusion method (Figure 9).

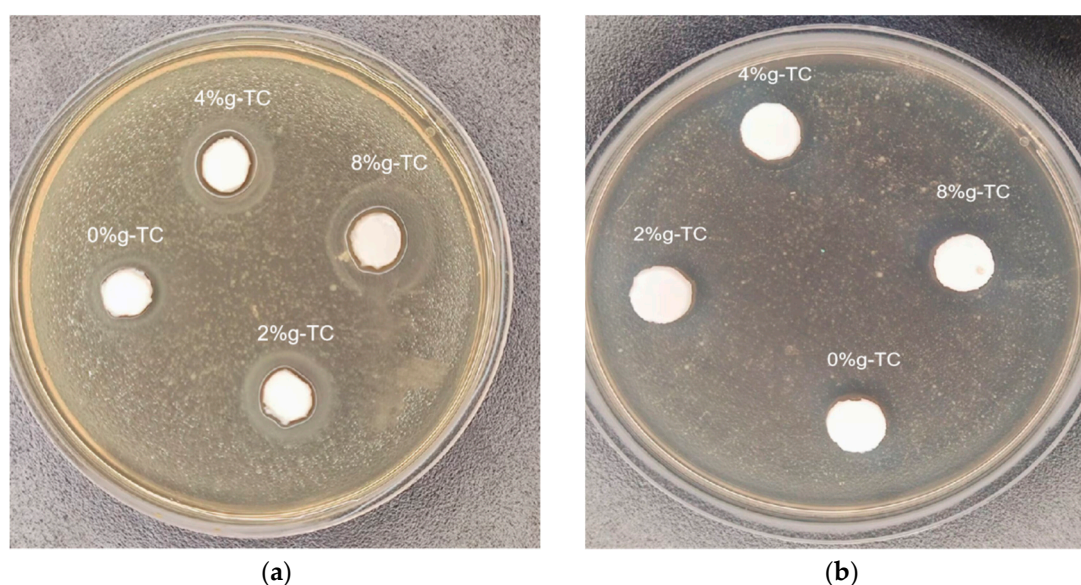


Figure 9. The antibacterial efficacy of the composite hydrogels against *S. aureus* (a) and *E. coli* (b).

A clear concentration-dependent antibacterial effect was observed. The pure PVA/SA hydrogel showed a very slight inhibitory zone, which could be attributed to the mild inherent bacteriostatic property of alginate or its physical barrier effect. However, with increasing content of 200CN/1TC (2%, 4%, 8%), the inhibition zones against both bacterial strains progressively enlarged and became more distinct. Notably, the 8% 200CN/1TC composite hydrogel demonstrated the most significant antibacterial activity, forming inhibition zones of 12.3 mm against *S. aureus* and 10.8 mm against *E. coli*, respectively. These results directly correlate with the photocatalytic performance observed in the intracellular ROS generation under light, confirming that enhanced photoactivity under light irradiation is the primary driver of the antibacterial efficacy.

The significantly enhanced antibacterial efficacy of the 200CN/1TC composite hydrogel is attributed to a multifactorial and synergistic mechanism. Under visible light illumination, CN acts as a photosensitizer, while the conductive TC promotes charge separation, substantially boosting ROS generation ($\bullet\text{O}_2^-$, $\bullet\text{OH}$). Notably, the observed antibacterial inhibition zones under light correspond to the ROS levels quantified via DCFH-DA assay, establishing a direct link between the photoactivity of the material and its ability to induce

oxidative damage in bacteria. Furthermore, the sharp, two-dimensional edges of the TC nanosheets contribute a physical “nanoknife” effect, capable of mechanically disrupting the integrity of bacterial cell walls and membranes, leading to content leakage and cell death. This physical action complements the photocatalytic ROS generation, providing a dual-mode attack against structurally diverse pathogens. The composite demonstrates remarkable broad-spectrum efficacy against both Gram-negative *E. coli* and Gram-positive *S. aureus*, overcoming their distinct membrane barriers—the outer membrane in Gram-negative bacteria and the thick peptidoglycan layer in Gram-positive strains. The PVA/SA hydrogel matrix further enhances this synergistic performance by serving as a sustained-release platform that maintains high local nanosheet concentration at the infection site, thereby ensuring prolonged antibacterial activity and establishing the composite as a promising candidate for combating diverse bacterial infections. Collectively, these results demonstrate that the light-triggered photoactivity of the 200CN/1TC nanocomposite is central to its broad-spectrum antibacterial function, with structural differences between Gram-positive and Gram-negative bacteria modulating the extent of photodynamic inactivation.

3. Conclusions

- A novel multifunctional hydrogel system was successfully fabricated by integrating electron beam-irradiated CN with TC into a PVA/SA matrix, achieving uniform nanomaterial dispersion and strong interfacial interactions.
- The composite hydrogel exhibited improved mechanical properties (tensile strength up to 2.1 ± 0.3 MPa) and tunable swelling behavior, while maintaining excellent biocompatibility, with cell viability above 80% across all tested concentrations under light exposure.
- The hydrogel demonstrated significant light-induced ROS generation and concentration-dependent broad-spectrum antibacterial activity, with inhibition zones up to 12.3 mm (*S. aureus*) and 10.8 mm (*E. coli*), attributed to synergistic photocatalytic ROS generation and MXene-mediated physical disruption under visible light.
- This work provides a promising strategy for designing mechanically robust and photoresponsive wound dressings capable of addressing bacterial resistance through dual-mode antibacterial action while ensuring high biosafety.

4. Materials and Methods

4.1. Preparation of 200CN/1TC Composite Material

CN was first synthesized through thermal polymerization of urea. Briefly, 10.0 g of urea was dissolved in 20 mL of deionized water under ultrasonication for 2 h. The solution was then vacuum-dried at 60 °C to obtain crystalline solids. The obtained crystals were heated in a tube furnace under a nitrogen atmosphere at 550 °C for 2 h with a heating and cooling rate of 10 °C·min^{−1}, yielding CN.

CN was subsequently modified via electron beam irradiation. In a typical process, 0.12 g of as-prepared CN was mixed with 12 mL of isopropanol, 120 µL of water, and 240 µL of ammonia. The mixture was ultrasonicated three times (10 min each) and then sealed in a polyethylene bag. It was irradiated under an electron beam at a dose of 200 kGy. The product was washed several times with ethanol and deionized water, and finally dried at 60 °C under vacuum.

The 200CN/1TC nanocomposite was prepared by dispersing 0.1 g of the irradiated CN (denoted as 200CN) in deionized water under 2 h of ultrasonication. Separately, 1 wt% TC was dispersed in 10 mL deionized water via 15 min of sonication. TC suspension was then added dropwise to the 200CN dispersion, and the mixture was further ultrasonicated for 4 h. The precipitate was collected by centrifugation and dried at 60 °C for 12 h.

Finally, a PVA/SA hydrogel incorporated with 200CN/1TC nanocomposite was fabricated. 10 g of PVA was dissolved in 100 mL deionized water at 100 °C under magnetic stirring. Then, 0.5 g of SA was gradually added, and stirring continued for 2 h until complete dissolution. Different amounts of 200CN/1TC were blended into the PVA/SA solution under stirring. The mixture was injected into a Petri dish to form a 4–5 mm thick layer, which was subjected to three freeze-thaw cycles (freezing at −20 °C for 3 h and thawing at room temperature for 6 h per cycle) to obtain the final hydrogel.

4.2. Characterization

The chemical composition of the hydrogels was analyzed using FT-IR (Thermo Fisher Nicolet, Waltham, MA, USA). Crystal structures were examined by XRD (Shimadzu, Kyoto, Japan). UV-Vis diffuse reflectance spectra were collected on a solid-state spectrophotometer (UV-3600, Shimadzu, Kyoto, Japan). Specific surface area and pore size distribution were determined via nitrogen adsorption–desorption measurements performed on a surface area analyzer (NOVA TOUCH LX1, Anton Paar, Graz, Austria). The microporous morphology of the lyophilized hydrogels was observed by scanning electron microscopy (SEM, TESCAN MIRA LMS, Tescan, Brno, Czech Republic). Thermal stability was evaluated by TGA on a TGA-8000 (TG 209F3, NETZSC, Germany). The TGA measurements were performed under a nitrogen atmosphere (flow rate: 20 mL·min^{−1}) with a heating rate of 10 °C·min^{−1} from room temperature to 800 °C, using approximately 5–10 mg of each dried sample. The tensile strength of the hydrogel strips (length: 30 mm, width: 5 mm, thickness: 2 mm) was measured using a universal testing machine (KZ-DSC-500, Suzhou Kezhun Measurement & Control Co., Ltd., Suzhou, China) at a crosshead speed of 10 mm·min^{−1}. The equilibrium swelling ratio was determined by immersing the dried hydrogels in phosphate-buffered saline (PBS, pH 7.4) at 37 °C until constant weight, and calculated as $(W_s - W_0)/W_0$, where W_0 and W_s are the weights of the dry and swollen samples, respectively.

4.3. Cytotoxicity Assay

L929 fibroblasts, obtained from the American Type Culture Collection (ATCC), were seeded into a 96-well plate and allowed to adhere. After cell attachment, the culture medium was replaced with extracts of the composite hydrogels containing varying concentrations of the 200CN/1TC nanomaterial. Following 24 h of incubation, the extract was removed, and 100 µL of MTT solution (5 µg/mL) was added to each well. The plates were further incubated for 4 h. Thereafter, the MTT solution was aspirated, and 100 µL of dimethyl sulfoxide (DMSO) was added to each well to dissolve the formazan crystals. The plates were shaken for 10 min to ensure complete dissolution. The optical density (OD) of the solution in each well was measured at a wavelength of 570 nm using a microplate reader. The cell viability rate was calculated based on the OD values.

4.4. Intracellular ROS Assay

The intracellular ROS generation induced by the composite hydrogels was evaluated using the fluorescent probe 2',7'-dichlorodihydrofluorescein diacetate (DCFH-DA). L929 fibroblasts were seeded in 24-well plates at a density of 5×10^4 cells per well and cultured for 24 h. Subsequently, the culture medium was replaced with hydrogel extracts containing 0%, 2%, 4%, and 8% 200CN/1TC nanocomposite, and the cells were incubated for another 24 h under light or dark conditions. During the incubation period, the light-treated groups were irradiated with a 670 nm laser (0.45 W/cm²) for 10 min at the midpoint of the 24-h incubation, while dark groups were kept in the dark under otherwise identical conditions. After the 24-h incubation, the extract was removed and the cells were washed twice with PBS. Subsequently, the cells were incubated with 10 µM DCFH-DA in serum-free medium at 37 °C for 20 min in the dark. Following probe loading, the cells were washed twice

with PBS to remove excess dye. Fluorescence images were immediately captured using an inverted fluorescence microscope.

4.5. Antibacterial Performance Test

The antibacterial properties of the composite hydrogels incorporating different concentrations of the 200CN/1TC nanomaterial were evaluated against *E. coli* and *S. aureus* using the agar diffusion method. A liquid bacterial culture medium was prepared containing 1 g/100 mL peptone, 0.3 g/100 mL beef extract, and 0.5 g/100 mL sodium chloride in distilled water. One milliliter of frozen stock bacterial suspension each of *E. coli* and *S. aureus* was inoculated into the prepared medium, respectively. The inoculated media were then incubated in a shaker at 37 °C for approximately 10 h for bacterial growth. The resulting bacterial suspensions were diluted to a concentration of 10⁵ CFU/mL for use as the working suspensions.

A solid culture medium was prepared by mixing 1 g/100 mL peptone, 1 g/100 mL sodium chloride, 0.5 g/100 mL yeast extract, and 1.5 g/100 mL agar in distilled water. The mixture was sterilized by autoclaving at 121 °C for 30 min, ensuring both sterilization and complete mixing of the components. The sterilized medium was poured into sterile Petri dishes and allowed to cool and solidify. The prepared bacterial suspensions were uniformly spread onto the surfaces of the solid agar plates. Hydrogel samples of different compositions were cut into 8 mm diameter discs and placed onto the inoculated agar surfaces. The plates were incubated at 37 °C for 10 h, after which the sizes of the inhibition zones were observed and recorded.

Author Contributions: Conceptualization, H.C. and B.H.; methodology, Y.W.; formal analysis, K.X.; investigation, Y.Z.; resources, J.L.; data curation, Z.S.; writing—original draft preparation, R.F. and X.C.; writing—review and editing, H.C. and B.H.; supervision, H.C.; project administration, B.H.; funding acquisition, B.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Hubei Provincial Natural Science Foundation, grant number 2024AFC063; Natural Science Foundation of Xianning City, grant number 2025DJK08; School of Stomatology and Optometry, Hubei University of Science and Technology, grant number 2021WG09.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy.

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

References

1. Li, B.; Liao, Y.; Su, X.; Chen, S.; Wang, X.; Shen, B.; Song, H.; Yue, P. Powering Mesoporous Silica Nanoparticles into Bioactive Nanoplatforams for Antibacterial Therapies: Strategies and Challenges. *J. Nanobiotechnol.* **2023**, *21*, 325. [CrossRef]
2. Theuretzbacher, U.; Baraldi, E.; Ciabusch, F.; Callegari, S. Challenges and Shortcomings of Antibacterial Discovery Projects. *Clin. Microbiol. Infect.* **2023**, *29*, 610–615. [CrossRef]
3. Zhang, Y.; Luo, M.; Shi, X.; Li, A.; Zhou, W.; Yin, Y.; Wang, H.; Wong, W.-L.; Feng, X.; He, Q. Pyrgos[n]Cages: Redefining Antibacterial Strategy against Drug Resistance. *Sci. Adv.* **2024**, *10*, eadp4872. [CrossRef]
4. Li, X.; Jing, X.; Yu, Z.; Huang, Y. Diverse Antibacterial Treatments beyond Antibiotics for Diabetic Foot Ulcer Therapy. *Adv. Healthc. Mater.* **2023**, *12*, 2300375. [CrossRef] [PubMed]
5. Liu, X.-Y.; Li, R.-F.; Jia, J.; Yu, Z.-L. Antibacterial Micro/Nanomotors: Current Research Progress, Challenges, and Opportunities. *Theranostics* **2024**, *14*, 1029–1048. [CrossRef]
6. Zhang, Y.; Hu, X.; Shang, J.; Shao, W.; Jin, L.; Quan, C.; Li, J. Emerging Nanozyme-Based Multimodal Synergistic Therapies in Combating Bacterial Infections. *Theranostics* **2022**, *12*, 5995–6020. [CrossRef]

7. Mei, L.; Zhu, S.; Yin, W.; Chen, C.; Nie, G.; Gu, Z.; Zhao, Y. Two-Dimensional Nanomaterials beyond Graphene for Antibacterial Applications: Current Progress and Future Perspectives. *Theranostics* **2020**, *10*, 757–781. [[CrossRef](#)]
8. Talreja, N.; Chauhan, D.; Ashfaq, M. Photo-Antibacterial Activity of Two-Dimensional (2D)-Based Hybrid Materials: Effective Treatment Strategy for Controlling Bacterial Infection. *Antibiotics* **2023**, *12*, 398. [[CrossRef](#)] [[PubMed](#)]
9. Zhao, J.; Huang, S.; Ravisankar, P.; Zhu, H. Two-Dimensional Nanomaterials for Photoinduced Antibacterial Applications. *ACS Appl. Bio Mater.* **2020**, *3*, 8188–8210. [[CrossRef](#)]
10. Ma, D.; Zhang, Z.; Zou, Y.; Chen, J.; Shi, J.-W. The Progress of G-C₃N₄ in Photocatalytic H₂ Evolution: From Fabrication to Modification. *Coord. Chem. Rev.* **2024**, *500*, 215489. [[CrossRef](#)]
11. Kong, X.; Liu, X.; Zheng, Y.; Chu, P.K.; Zhang, Y.; Wu, S. Graphitic Carbon Nitride-Based Materials for Photocatalytic Antibacterial Application. *Mater. Sci. Eng. R Rep.* **2021**, *145*, 100610. [[CrossRef](#)]
12. Chen, Y.; Cheng, M.; Lai, C.; Wei, Z.; Zhang, G.; Li, L.; Tang, C.; Du, L.; Wang, G.; Liu, H. The Collision between g-C₃N₄ and QDs in the Fields of Energy and Environment: Synergistic Effects for Efficient Photocatalysis. *Small* **2023**, *19*, 2205902. [[CrossRef](#)]
13. Chuaicham, C.; Pawar, R.R.; Karthikeyan, S.; Ohtani, B.; Sasaki, K. Fabrication and Characterization of Ternary Sepiolite/g-C₃N₄/Pd Composites for Improvement of Photocatalytic Degradation of Ciprofloxacin under Visible Light Irradiation. *J. Colloid Interface Sci.* **2020**, *577*, 397–405. [[CrossRef](#)] [[PubMed](#)]
14. Chen, X.; Weng, M.; Lan, M.; Weng, Z.; Wang, J.; Guo, L.; Lin, Z.; Qiu, B. Superior Antibacterial Activity of Sulfur-Doped g-C₃N₄ Nanosheets Dispersed by *Tetrastigma hemsleyanum* Diels & Gilb's Polysaccharides-3 Solution. *Int. J. Biol. Macromol.* **2021**, *168*, 453–463. [[CrossRef](#)] [[PubMed](#)]
15. Deng, Y.; Ouyang, X.; Sun, J.; Shi, X.; Li, Y.; Chan, Y.K.; Yang, W.; Peng, S. Rapid Sterilisation and Diabetic Cutaneous Regeneration Using Cascade Bio-Heterojunctions through Glucose Oxidase-Primed Therapy. *Bioact. Mater.* **2023**, *25*, 748–765. [[CrossRef](#)] [[PubMed](#)]
16. Jhanani, G.K.; Al-Ansari, M.M.; Lee, J.; Sathiyamoorthi, E.; Karuppusamy, I. Photocatalytic Removal of Benzo[a]Pyrene and Antibacterial Efficacy of Graphitic Carbon Nitride-Silver-Nickel (g-C₃N₄-Ag-Ni) Mediated Nanocomposites. *Chemosphere* **2024**, *350*, 141122. [[CrossRef](#)]
17. Chen, X.; Shi, Z.; Tian, Y.; Lin, P.; Wu, D.; Li, X.; Dong, B.; Xu, W.; Fang, X. Two-Dimensional Ti₃C₂ MXene-Based Nanostructures for Emerging Optoelectronic Applications. *Mater. Horiz.* **2021**, *8*, 2929–2963. [[CrossRef](#)]
18. Amara, U.; Hussain, I.; Ahmad, M.; Mahmood, K.; Zhang, K. 2D MXene-Based Biosensing: A Review. *Small* **2023**, *19*, 2205249. [[CrossRef](#)]
19. Gao, F.; Xue, C.; Zhang, T.; Zhang, L.; Zhu, G.; Ou, C.; Zhang, Y.; Dong, X. MXene-Based Functional Platforms for Tumor Therapy. *Adv. Mater.* **2023**, *35*, 2302559. [[CrossRef](#)]
20. Eom, W.; Shin, H.; Jeong, W.; Ambade, R.B.; Lee, H.; Han, T.H. Surface Nitrided MXene Sheets with Outstanding Electroconductivity and Oxidation Stability. *Mater. Horiz.* **2023**, *10*, 4892–4902. [[CrossRef](#)]
21. Sang, X.; Xie, Y.; Yilmaz, D.E.; Lotfi, R.; Alhabeb, M.; Ostadhossein, A.; Anasori, B.; Sun, W.; Li, X.; Xiao, K.; et al. In Situ Atomistic Insight into the Growth Mechanisms of Single Layer 2D Transition Metal Carbides. *Nat. Commun.* **2018**, *9*, 2266. [[CrossRef](#)]
22. Huang, W.-X.; Li, Z.-P.; Li, D.-D.; Hu, Z.-H.; Wu, C.; Lv, K.-L.; Li, Q. Ti₃C₂ MXene: Recent Progress in Its Fundamentals, Synthesis, and Applications. *Rare Met.* **2022**, *41*, 3268–3300. [[CrossRef](#)]
23. Su, T.; Hood, Z.D.; Naguib, M.; Bai, L.; Luo, S.; Rouleau, C.M.; Ivanov, I.N.; Ji, H.; Qin, Z.; Wu, Z. 2D/2D Heterojunction of Ti₃C₂/g-C₃N₄ Nanosheets for Enhanced Photocatalytic Hydrogen Evolution. *Nanoscale* **2019**, *11*, 8138–8149. [[CrossRef](#)]
24. Kumar, A.; Majithia, P.; Choudhary, P.; Mabbett, I.; Kuehnel, M.F.; Pitchaimuthu, S.; Krishnan, V. MXene Coupled Graphitic Carbon Nitride Nanosheets Based Plasmonic Photocatalysts for Removal of Pharmaceutical Pollutant. *Chemosphere* **2022**, *308*, 136297. [[CrossRef](#)]
25. Iravani, S.; Varma, R.S. MXene-Based Composites against Antibiotic-Resistant Bacteria: Current Trends and Future Perspectives. *RSC Adv.* **2023**, *13*, 9665–9677. [[CrossRef](#)] [[PubMed](#)]
26. Zhang, D.-Y.; Wang, M.-X.; Cai, C.; Cheng, W.-W.; Cheng, Y.-J.; Liu, W.-L.; Huang, R.; Zhang, A.-Q.; Qin, S.-Y. Bacterial Membrane-Anchored Lipopeptide/MXene Nanoplatfrom for Tri-Modal Therapy toward Bacteria-Infected Diabetic Wound. *Biomater. Adv.* **2025**, *175*, 214324. [[CrossRef](#)] [[PubMed](#)]
27. Seidi, F.; Arabi Shamsabadi, A.; Dadashi Firouzjaei, M.; Elliott, M.; Saeb, M.R.; Huang, Y.; Li, C.; Xiao, H.; Anasori, B. MXenes Antibacterial Properties and Applications: A Review and Perspective. *Small* **2023**, *19*, 2206716. [[CrossRef](#)] [[PubMed](#)]
28. Chin, S.F.; Romainor, A.N.B.; Pang, S.C.; Lihan, S. Antimicrobial Starch-Citrate Hydrogel for Potential Applications as Drug Delivery Carriers. *J. Drug Deliv. Sci. Technol.* **2019**, *54*, 101239. [[CrossRef](#)]
29. González-Henríquez, C.; Sarabia-Vallejos, M.; Rodríguez-Hernandez, J. Advances in the Fabrication of Antimicrobial Hydrogels for Biomedical Applications. *Materials* **2017**, *10*, 232. [[CrossRef](#)]
30. Hao, Z.; Li, X.; Zhang, R.; Zhang, L. Stimuli-Responsive Hydrogels for Antibacterial Applications. *Adv. Healthc. Mater.* **2024**, *13*, 2400513. [[CrossRef](#)]

31. Li, S.; Dong, S.; Xu, W.; Tu, S.; Yan, L.; Zhao, C.; Ding, J.; Chen, X. Antibacterial Hydrogels. *Adv. Sci.* **2018**, *5*, 1700527. [[CrossRef](#)] [[PubMed](#)]
32. Tang, Y.; Xu, H.; Wang, X.; Dong, S.; Guo, L.; Zhang, S.; Yang, X.; Liu, C.; Jiang, X.; Kan, M.; et al. Advances in Preparation and Application of Antibacterial Hydrogels. *J. Nanobiotechnol.* **2023**, *21*, 300. [[CrossRef](#)] [[PubMed](#)]
33. Pierau, L.; Versace, D.-L. Light and Hydrogels: A New Generation of Antimicrobial Materials. *Materials* **2021**, *14*, 787. [[CrossRef](#)]
34. Li, X.; Zhang, L.; Liu, Z.; Wang, R.; Jiao, T. Recent Progress in Hydrogels Combined with Phototherapy for Bacterial Infection: A Review. *Int. J. Biol. Macromol.* **2024**, *274*, 133375. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.