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Highly Active and Durable Bimetallic CoMnO_x Catalyst Supported on Carbon Nanofibers for Peroxymonosulfate Activation toward Water Treatment

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A bimetallic CoMnO_x catalyst supported on carbon nanofibers has been constructed through a co-precipitation protocol coupled with controlled low-temperature calcination treatment. The optimized catalyst exhibits remarkable peroxyomonosulfate (PMS) activation property toward Rhodamine (RhB) degradation, where ${}^1\text{O}_2$ is identified as the dominant reactive oxygen species (ROS).

In contemporary water treatment technologies, the effective and targeted elimination of hazardous contaminants is substantially challenging.¹ In recent years, peroxyomonosulfate (PMS)-activated oxidation systems have emerged as a prominent research focus in advanced oxidation processes (AOPs), demonstrating remarkable potential for environmental remediation.^{2,3} Reactive oxygen species (ROS), including free radicals like hydroxyl radicals ($\bullet\text{OH}$) and sulfate radicals ($\text{SO}_4^{\bullet-}$), as well as non-radical species, can be generated from PMS molecule with an asymmetric structure.⁴ In comparison to radical-based ROS, ${}^1\text{O}_2$ emerges as a particularly attractive oxidant in AOPs due to its inherent benefits including prolonged longevity, broad pH tolerance, robust electrophilicity, and exceptional target specificity.⁵

Defect engineering has proved to be a promising strategy to promote catalytic efficiencies in Fenton-like reactions. Upon oxygen vacancy formation, electrons adjacent to the defect sites undergo delocalization. This critical electronic restructuring process not only significantly enhances surface activation but also concurrently improves charge transfer capability and electrical conductivity. Consequently, transition metal oxides enriched with oxygen vacancies exhibit exceptional PMS activation efficiency in Fenton-like systems.⁶ In a typical example, Zhu et al. introduced oxygen vacancies on commercial MnO_2 surfaces under ambient atmospheric conditions. The resulting defect-rich MnO_2 exhibited enhanced catalytic performance in PMS activation, achieving complete mineralization of tetrabromobisphenol (TBBPA) with a remarkable pseudo-first-order rate constant of 0.21 min^{-1} , a

notable 22-fold enhancement compared to pristine MnO_2 .⁷ Although metal oxide-activated persulfate system exhibited advantageous characteristics such as mild reaction conditions, cost-effectiveness, and high efficiency,⁸ they often suffer from the obstacles of the agglomeration of active components, which leads to diminished catalytic efficacy and durability. The integration of carbon-based materials hold promise for bolstering the electron transfer capacity of metal oxide components and establishing robust covalent bonds between carbon carriers and metal elements, ultimately enhancing the stability of catalysts.⁹

Inspired by the preceding discussions, we propose an innovative defect engineering strategy that synergistically integrates bimetallic oxide architecture with oxygen vacancy modulation, yielding $\text{CNFs@CoMnO}_x\text{-500}$ catalyst featuring exceptional PMS activation efficiency. The study also delved into the examination of various influential factors, including catalyst and PMS dosage, pH of the solution, co-existing anions, natural organic matter, among others. Concurrently, the generated ROS species are identified through quenching experiments and electron paramagnetic resonance (EPR) spectroscopy analysis. The findings demonstrate the effectiveness of the CNFs@CoMnO_x catalyst for Rhodamine (RhB) degradation via non-radical pathways, specifically ${}^1\text{O}_2$ species.

The synthesis procedure and structural evolution of $\text{CNFs@CoMnO}_x\text{-500}$ composite are illustrated in Fig. 1, which involves a co-deposition strategy followed by controlled thermal annealing at $500\text{ }^\circ\text{C}$ under inert atmosphere. During the initial deposition process, a critical redox reaction occurs KMnO_4 and carbon leads to the deposition of MnO_2 nanosheets onto CNFs ($4\text{MnO}_4^- + 3\text{C} + \text{H}_2\text{O} \rightarrow 4\text{MnO}_2 + \text{CO}_3^{2-} + 2\text{HCO}_3^-$).¹⁰ As depicted in Fig. S1a and b, bare CNFs display smooth surfaces with uniform nanofibrous morphology, featuring an average diameter of 152 nm . Subsequent precursor integration through sequential treatment with $\text{Co}(\text{NO}_3)_2$ and KMnO_4 solutions induces uniform growth of two-dimensional nanosheet

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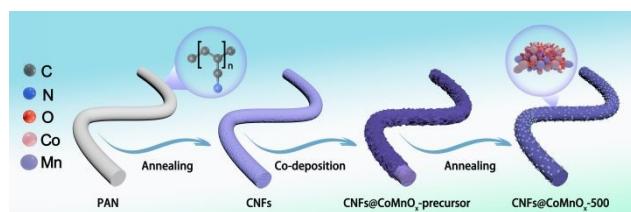


Fig. 1 Schematic diagram for the synthetic process of CNFs@CoMnO_x-500 nanofibers.

architectures on the surface of CNFs, resulting in a notable diameter increase to 180 nm (Fig. 2a and S1c). TEM characterization further confirms the coherent growth of the hierarchical nanostructures, revealing well-defined interfacial contact between the CNF core and the deposited MnCoO_x-precursor phases (Fig. S2). Upon annealing at 500 °C, the surface morphology of CNFs@CoMnO_x-precursor undergoes a dramatic transformation from nanosheets to nanoparticles, with the average diameter reduced to 158 nm (Fig. 2b, c and S1d). Consistent with this observation, Fig. S3-S6 demonstrate that the elevated annealing temperature leads to progressively refined nanoparticle structure of CoMnO_x. For comparison, when solely KMnO₄ is introduced into the reaction system, thin nanosheets form on the surface of the CNFs (Fig. S7a), which evolve into nanoparticles following low-temperature annealing treatment (Fig. S7b). In contrast, the presence of Co²⁺ alone induces minimal nanosheet deposition on the CNFs surface, with negligible morphological alterations observed before and after thermal treatment (Fig. S7c and d). The structure evolution of the catalysts series is analyzed by XRD measurement. As illustrated in Fig. S8, the precursors exhibit amorphous characteristics prior to annealing. Upon annealing at 400 °C, the XRD patterns resolve two distinct crystalline phases: (Co,Mn)(Co,Mn)₂O₄ and CoO. With increasing annealing temperatures to 500 °C and 600 °C, the diffraction peaks of the products position between those of CoO (JCPDS # 70-2856) and

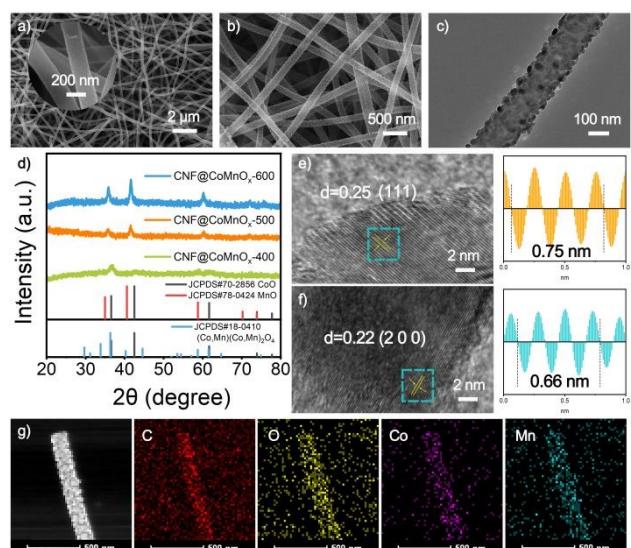


Fig. 2 (a) FESEM image of CNFs@CoMnO_x-precursor nanofibers. (b,c) FESEM and TEM image; (d) XRD patterns; (e,f) HRTEM image; (g) HAADF-STEM and EDX mappings of CNFs@CoMnO_x-500.

MnO (JCPDS # 78-0424), with no secondary phases detected (Fig. 2d). This phase progression confirms the formation of bimetallic CoMnO_x solid solution structure on CNFs.¹¹ Raman spectroscopy further corroborates the structural evolution of the obtained CNFs@CoMnO_x-500. The Mn–O stretching vibration in CNFs@MnO_x-500 appears at 656 cm⁻¹, while in the CNFs@CoMnO_x-precursor and CNFs@CoMnO_x-500 samples, this band exhibits a marked shift, suggesting the incorporation of Co species into the lattice (Fig. S9).¹² HRTEM analysis further reveals well-defined lattice fringes with measured interplanar spacings of 0.25 nm and 0.22 nm, corresponding to the (111) and (200) crystallographic planes of CNFs@CoMnO_x-500, respectively (Fig. 2e and f). Energy-dispersive X-ray (EDX) spectroscopy confirms the coexistence of Co, Mn, O, C, and N elements in CNFs@CoMnO_x-500 sample (Fig. S10), while the elemental mapping demonstrates their spatially homogeneous distribution across the nanostructure (Fig. 2g). The EPR analysis reveals that the CNFs@CoMnO_x-precursor sample exhibits a characteristic signal at $g = 2.003$ (Fig. S11a), which is typically associated with unpaired electrons trapped at oxygen vacancies.¹³ Complementary XPS deconvolution of the O 1s spectra resolves three distinct contributions including lattice oxygen (O_{lat}) at 530.2 eV, oxygen vacancy at 531.3 eV, and surface-adsorbed hydroxyl species from H₂O (O_{H2O}) at 532.2 eV (Fig. S11b).¹⁴ Comparative quantification reveals that both CNFs@CoMnO_x-400 (29.7%) and CNFs@CoMnO_x-500 (28.4%) exhibit significantly elevated oxygen vacancy fractions relative to CNFs@CoMnO_x-600 (21.6%). It can be concluded that the oxygen vacancy concentration decreases in the following order: CNFs@CoMnO_x-400≈CNFs@CoMnO_x-500>CNFs@CoMnO_x-600. The chemical valence states of various crystalline materials are further investigated by Co 2p and Mn 2p XPS spectra. As illustrated in Fig. S12a, the Mn 2p spectrum exhibits two primary spin-orbit components of Mn 2p_{1/2} at 653.4 eV and Mn 2p_{3/2} at 642.1 eV, respectively. High-resolution fitting of the Mn 2p_{3/2} identifies three distinct oxidation states of Mn²⁺ (641.1 eV), Mn³⁺ (642.5 eV), and Mn⁴⁺ (644.1 eV).¹⁵ The Co 2p exhibits characteristic peaks at 782.2 eV (Co²⁺ 2p_{3/2}) and 796.9 eV (Co²⁺ 2p_{1/2}), with additional features at 780.5 eV (Co³⁺ 2p_{3/2}) and 795.6 eV (Co³⁺ 2p_{1/2}), complemented by satellite peaks at 787.5 eV and 801.9 eV (Fig S12b).¹⁶ It can be seen that as the temperature increases, the oxidation states of Co and Mn decrease.

We systematically investigated the PMS activation capability of CNFs@CoMnO_x-500 toward RhB degradation, a typical model reaction for AOPs. Control experiments demonstrate negligible RhB degradation (below 5%) with CNFs@CoMnO_x-500 alone and <10% with PMS only (Fig. 3a). Strikingly, the first-order kinetic constant (k , min⁻¹) for RhB degradation is substantially enhanced in the CNFs@CoMnO_x-precursor/PMS system, reaching a value of 0.249 min⁻¹ (Fig. 3b, 3c and S13). The favorable catalytic performance of CNFs@CoMnO_x-precursor sample can be attributed to its oxygen vacancies. Notably, after the annealing treatment, the k value of the obtained CNFs@CoMnO_x-500 increases to 0.659 min⁻¹. This performance underscores the synergistic interplay



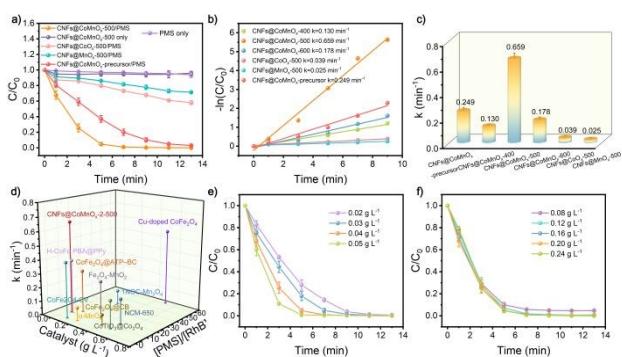


Fig. 3 (a) RhB degradation curves; (b) The corresponding fitted kinetics curves; (c) histogram of first-order kinetic constant values in varied catalytic reaction systems, (d) comparison of intrinsic catalytic activity of the CNFs@CoMnO_x-500 with reported catalysts towards PMS activation. Effect of (e) catalyst dosage, (f) PMS concentration on RhB degradation.

between the bimetallic solid solution architecture and oxygen vacancy in modulating redox-active sites. For comparative analysis, the catalytic performances in monometallic counterparts of CNFs@CoO_x-500 and CNFs@MnO_x-500 are suboptimal, achieving merely 42.0 % and 28.7% RhB degradation, respectively (Fig. 3a). As evidenced in Fig. 3d, the CNFs@CoMnO_x-500 catalyst also exhibits exceptional activity, surpassing numerous PMS-activated catalysts reported in the literature and positioning it as a leading candidate for high-efficiency AOPs. Additionally, the impact of catalyst dosage on RhB degradation efficiency is systematically evaluated (Fig. 3e). Results reveal that increasing the catalyst dosage from 0.02 to 0.04 g/L enhances RhB degradation rate from 0.345 min⁻¹ to 0.659 min⁻¹. Balancing catalytic efficacy with cost considerations, 0.04 g/L is identified as the optimal dosage for subsequent studies. Further investigation of PMS dosage effects (Fig. 3f) demonstrates a proportional improvement in RhB degradation kinetics within 0.08-0.20 g/L. However, when the PMS dosage reaches 0.24 g/L, a notable decline in degradation efficiency is observed, which is likely due to the PMS-PMS interactions producing less reactive species.¹⁷ Consequently, 0.20 g/L PMS is selected as the benchmark concentration to maximize oxidative radical utilization. The catalytic degradation rate exhibits a pronounced temperature dependence, increasing markedly with rising temperature (Fig. S14).¹⁸ Systematic evaluation across pH 3.0-11.0 reveals the broad operational versatility of the CNFs@CoMnO_x-500 catalyst, achieving complete RhB elimination at pH 5.0-9.0, whereas the degradation efficiency declines to 79.2% at pH 3.0 and 51.1% at pH 11.0 (Fig. S15a and b). As illustrated in Fig. S16, HCO₃⁻ notably suppresses RhB degradation in the CNFs@CoMnO_x-500/PMS system. This decreasing stems from that HCO₃⁻ scavenges reactive radicals (•SO₄⁻, •OH) to generate less oxidative CO₃²⁻, while simultaneously elevates solution pH to shift PMS speciation toward less reactive SO₅²⁻.¹⁹ Notably, the RhB efficiency remains robust against most of common anions and even humic acid, demonstrating remarkable tolerance to treat complex water. As shown in Fig. S17, the CNFs@CoMnO_x-500 catalyst demonstrates superior degradation performance across all tested dyes, yet exhibits marginally reduced efficacy

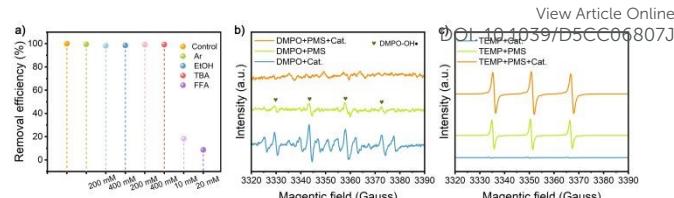


Fig. 4 (a) The quenching tests of CNFs@CoMnO_x-500/PMS system with diverse quenching agents. EPR spectra for (b) DMPO-•OH and (c) TEMP-¹O₂.

toward the antibiotic levofloxacin (LEVO). The slightly reduced degradation efficiency of CNFs@CoMnO_x-500 for RhB in complex aqueous environments can be attributed to its interference with co-existing ions (Fig. S18). The operational stability is rigorously assessed, revealing that the CNFs@CoMnO_x-500 catalyst maintains 97.1% RhB removal efficiency after five successive cycles, confirming its exceptional recyclability (Fig. S19). Post-catalysis characterization through XRD, SEM, and TEM analysis reveal the retention of structural integrity, with well-preserved crystallographic features and morphological stability (Fig. S20). Its practical implementation potential is evaluated in a membrane-based water purification platform (Fig. S21). Composite membranes are engineered via vacuum-assisted filtration of CNFs@CoMnO_x-500 suspensions onto polyvinylidene fluoride (PVDF) supports.²⁰ Performance analysis demonstrates that the pristine PVDF membrane displays limited initial RhB adsorption capacity and almost negligible adsorption after 140 min. In contrast, under continuous operation, the functionalized membrane with catalyst achieves sustained RhB degradation efficiency of 97.6%.

To identify the ROS involved in RhB degradation mediated by CNFs@CoMnO_x-500 catalyst, quenching experiments are systematically conducted. EtOH is recognized as an effective scavenger for both •OH and SO₄²⁻,²¹ while TBA is a selective scavenger for •OH, which are employed to assess radical contributions.²² As depicted in Fig. 4a and S22, both SO₄²⁻ and •OH scavengers demonstrate negligible inhibitory effects on the CNFs@CoMnO_x-500/PMS system, with degradation efficiency remaining largely unaffected even at elevated concentrations (200-400 mM). This finding suggests limited involvement of free SO₄²⁻ and •OH in the catalytic process. Complementary experiments with 10 mM FFA,^{23,24} demonstrates a significant 18.3% decrease in RhB removal efficiency, confirming the substantial involvement of ¹O₂ in the catalytic mechanism. Further investigation into ¹O₂ generation within the CNFs@CoMnO_x-500/PMS system is conducted to unravel the mechanistic pathways. The dependence on the dissolved oxygen is rigorously evaluated by purging the reaction medium with argon (Ar) for 30 min prior to catalytic activation. Notably, dissolved oxygen removal via Ar purging induces only minor slowdown in RhB degradation rate (Fig. S23). These observations conclusively exclude molecular oxygen as the predominant ¹O₂ precursor in this catalytic system.²⁵ EPR spectroscopy is further employed to identify ROS generated during PMS activation. Systematic spin-trapping experiments using DMPO for radical species detection (e.g., •OH and SO₄²⁻) and TEMP for ¹O₂ identification, revealing diagnostic spectral



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signatures.²⁶ The DMPO-PMS system exhibits characteristic 1:2:2:1 quadruplet signals, corresponding to DMPO-•OH adducts (Fig. 4b). Remarkably, the introduction of CNFs@CoMnO_x-500 into the DMPO-PMS system markedly attenuate these signals to near-background levels. In contrast, a prominent 1:1:1 triplet signal emerges in the TEMP-PMS system and an enhancement after the addition of CNFs@CoMnO_x-500 catalyst, providing unequivocal evidence of ¹O₂ generation (Fig. 4c). Control experiments reveal diminished ¹O₂ signals in catalyst-only system, demonstrating that ¹O₂ serves as the predominant reactive species governing RhB degradation in the CNFs@CoMnO_x-500/PMS system.

XPS analysis is used to elucidate the catalytic mechanism of the CNFs@CoMnO_x-500/PMS system. As illustrated in Fig. S24a, quantitative deconvolution reveals a discernible decrease in the Co²⁺ contribution from 39.4% to 37.2%, accompanied by a proportional increase in Co³⁺ content from 60.6% to 62.8% after the catalytic degradation reaction. This redox evolution indicates electron transfer from Co²⁺ to PMS during activation, with subsequent regeneration of Co²⁺ via reduction of Co³⁺ by HSO₅⁻ and SO₄²⁻ intermediate, thereby generating reactive SO₅²⁻ and OH• species.²⁷ For Mn species, quantitative XPS analysis reveals a notable valence state redistribution, indicating Mn-mediated electron redistribution process (Fig. S24b). Parallel characterization from XPS and EPR spectroscopy demonstrates a marked reduction in oxygen vacancy content from 28.4% to 19.7% after the catalytic degradation reaction. (Fig. S24c and S25), confirming the pivotal role of these structural defects in electron transfer mechanisms during redox cycling. Additionally, oxygen vacancy operates as PMS adsorption sites, facilitating electron transfer to surface-bound PMS, which increases the production of ROS.²⁸

The degradation mechanism of RhB is systematically elucidated by high-performance liquid chromatography mass spectrometer (HPLC-MS) measurement.²⁹ The primary degradation pathway initiates with sequential N-deethylation, consistent with established literature,³⁰ wherein RhB (m/z = 443) undergoes stepwise ethyl group elimination to yield P1 (m/z = 415) and P2 (m/z = 331) (Fig. S26 and 27). Subsequently cleavage induces chromophore destruction via dehydroxylation of product to produce P3, P4 and P5. Progressive fragmentation of these aromatic intermediates through bond scission and oxidation ultimately produces low-molecular-weight aliphatic compounds (P6–P8).

In this study, an oxygen vacancy-enriched CNFs@CoMnO_x-500 catalyst is strategically prepared via a co-precipitation protocol coupled with annealing process. The catalyst exhibits exceptional PMS activation capability, achieving an impressive 99% RhB degradation within 15 min. Mechanistic studies identify ¹O₂ as dominant ROS, with the oxygen vacancy-abundant interface facilitating PMS adsorption and electron shuttling. This work establishes a paradigm for designing multifunctional composite catalysts, offering critical guidelines for optimizing AOPs.

Author contributions

Siyu Ren: investigation, data curation and drafted the manuscript. Yue Zhang: investigation. Linfeng Zhang: investigation. Xiaofeng Lu: funding acquisition, resources, review & editing and supervision.

Conflict of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the ESI.

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Data availability statements

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The data supporting this article have been included as part of the Supplementary Information.

