

MXene/Carbon Cloth Electrodes for Electrochemical Activation of Peroxymonosulfate: A Sustainable Approach to Dye-Polluted Wastewater Treatment

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Abstract

A $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-coated carbon cloth (CC) anode aimed to develop for electrochemical activation of peroxymonosulfate (PMS) to degrade Methylene Blue (MB). MXene's high conductivity and catalytic surface terminations enhanced generation of $\text{SO}_4^{\bullet-}$ and -OH radicals ($\text{HSO}_5^- + e^- \rightarrow \text{SO}_4^{\bullet-} + \text{OH}^-$), achieving $\geq 95\%$ MB removal in ≤ 60 min with $\leq 1 \text{ kWh m}^{-3}$ energy under optimized pH, temperature, PMS concentration, and stirring rate via Box-Behnken RSM. The electrode retain performance over five cycles, offering a scalable, sludge-free solution for textile wastewater treatment.

Introduction

Textile industries discharge approximately 2.5 billion gallons of dye-contaminated wastewater annually, with Methylene Blue ($\text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S}$) representing a persistent cationic pollutant highly resistant to conventional biological and chemical treatments due to its stable aromatic structure. This study presents an innovative electrochemical advanced oxidation process (EAOP) utilizing dip-coated Mxene ($\text{Ti}_3\text{C}_2\text{T}_x$) on carbon cloth anodes for peroxymonosulfate (PMS) activation, targeting $\geq 95\%$ MB degradation within 60 minutes. The MXene coating enhances electrochemical performance through three synergistic mechanisms:

- metallic conductivity ($>15,000 \text{ S/cm}$) creates uniform current distribution and increased electroactive sites,
- hydrophilic surface terminations (-OH , -O , -F) catalytically lower PMS activation energy via $\text{HSO}_5^- + e^- \rightarrow \text{SO}_4^{\bullet-} + \text{OH}^-$, and
- layered morphology improves mass transfer of reactants to active sites.

The generated sulfate radicals ($\text{SO}_4^{\bullet-}$) and hydroxyl radicals (-OH) achieve complete mineralization:

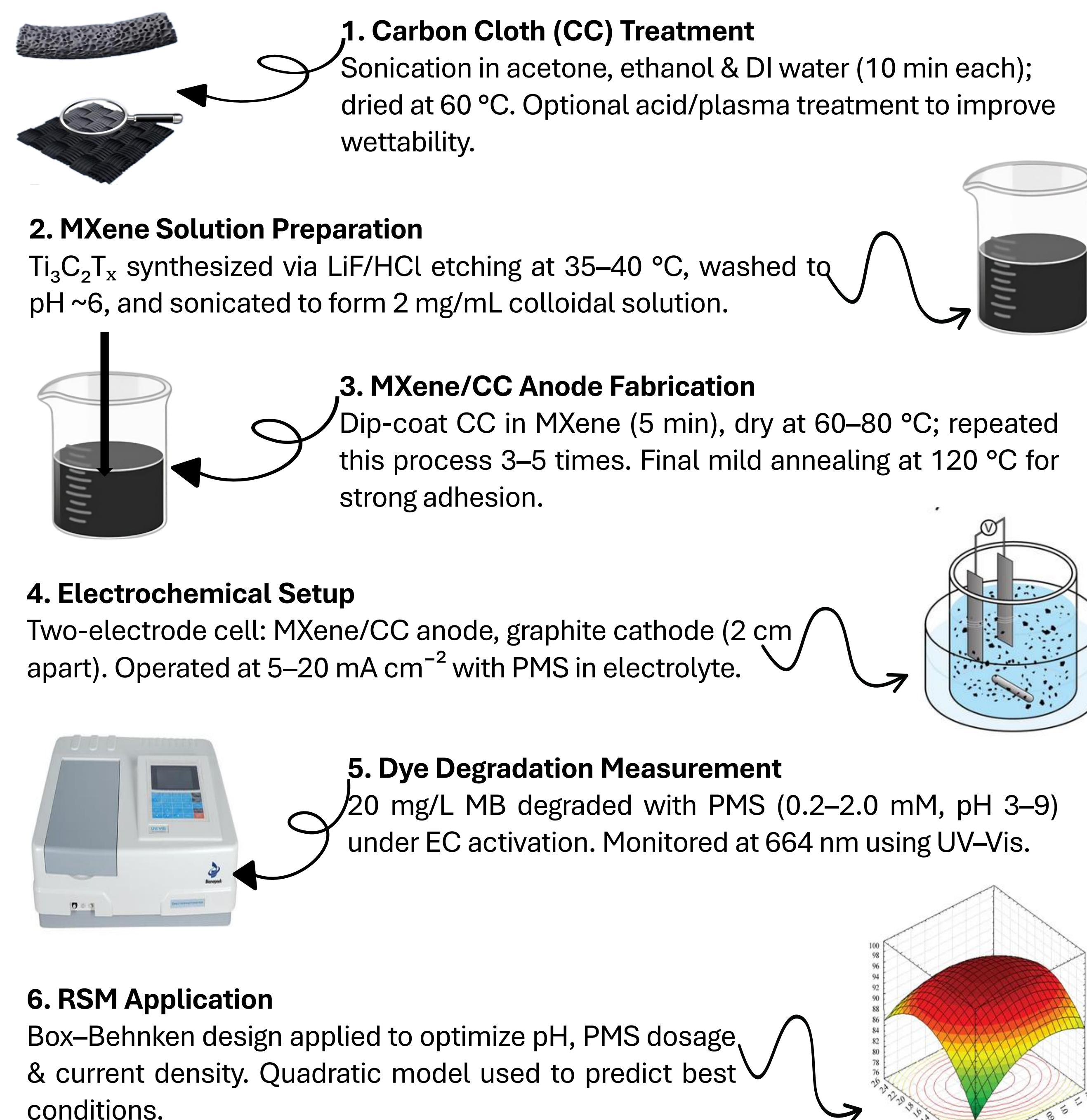
➤ $\text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S} + \text{ROS} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{harmless byproducts}$.

While Response Surface Methodology with Box-Behnken design optimizes pH, temperature, PMS concentration, and stirring rate to maximize removal efficiency while minimizing specific energy consumption ($\leq 1 \text{ kWh m}^{-3}$), establishing a sustainable, sludge-free treatment technology for textile wastewater remediation.

Objectives

- ❖ To fabricate and characterize $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-coated carbon cloth electrodes.
- ❖ To optimize pH, temperature, PMS concentration, and stirring rate via Box-Behnken RSM to achieve $\geq 95\%$ MB removal in ≤ 60 min with $\leq 1 \text{ kWh m}^{-3}$ energy.
- ❖ To validate optimum conditions and evaluate electrode stability over multiple cycles.

Methodology



Results

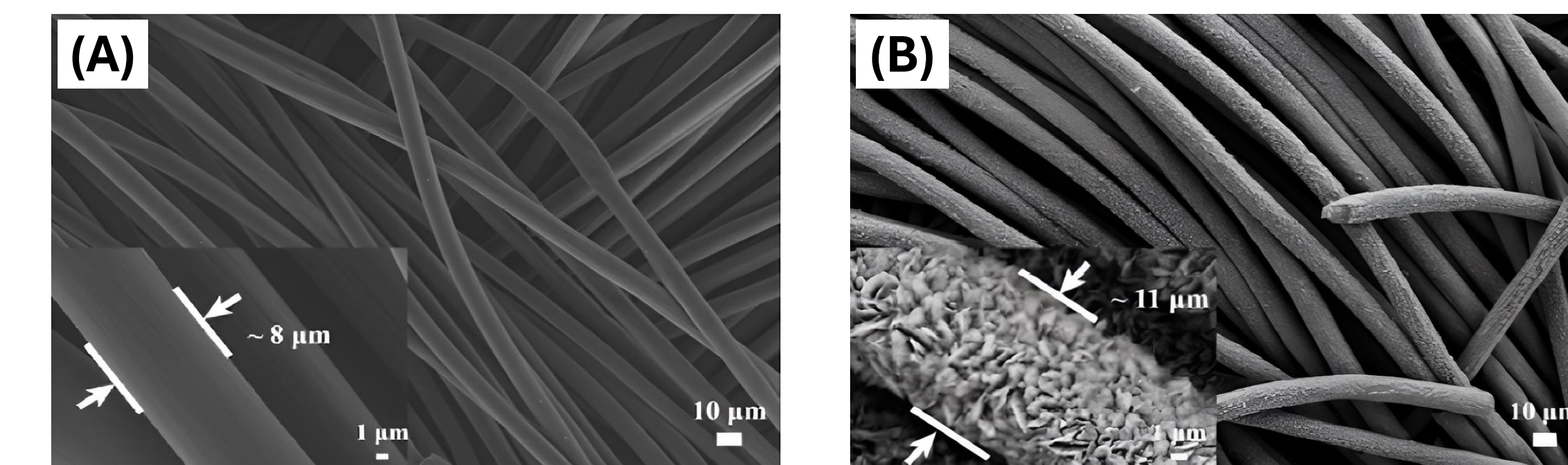


Fig. 1. SEM Image of (A) Pure CC and, (B) MXene/CC

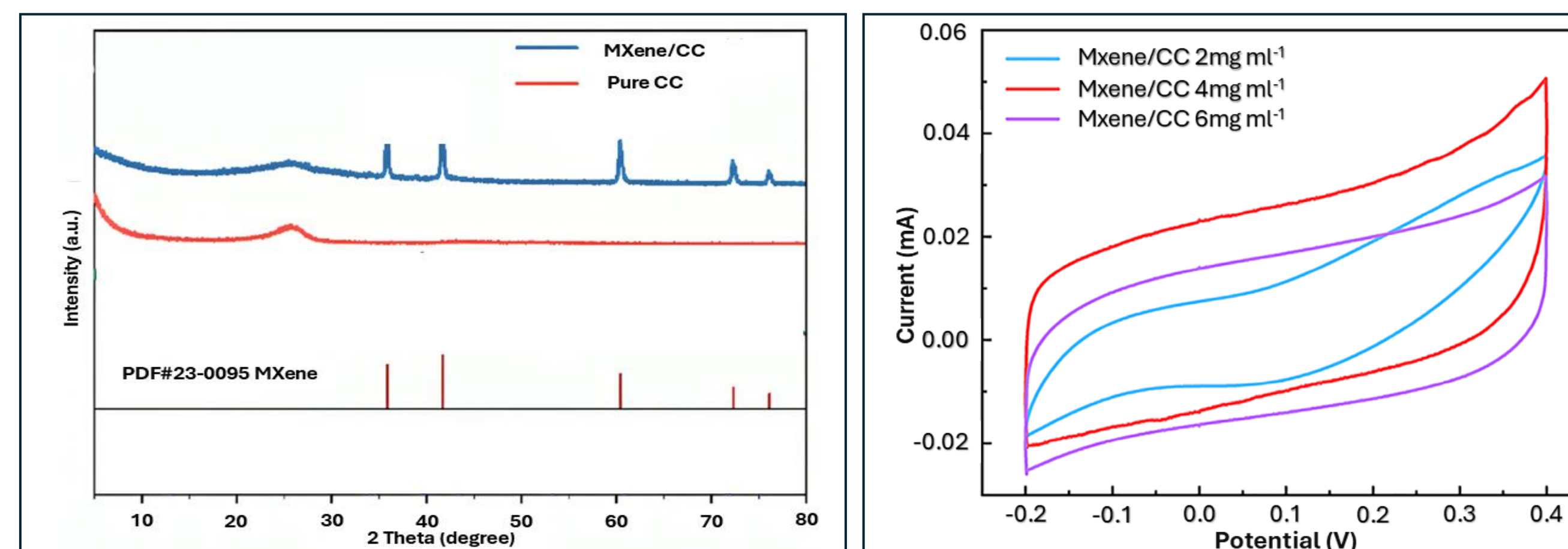


Fig. 2. XRD of Sample

Fig. 3. CVs of CC with MXene

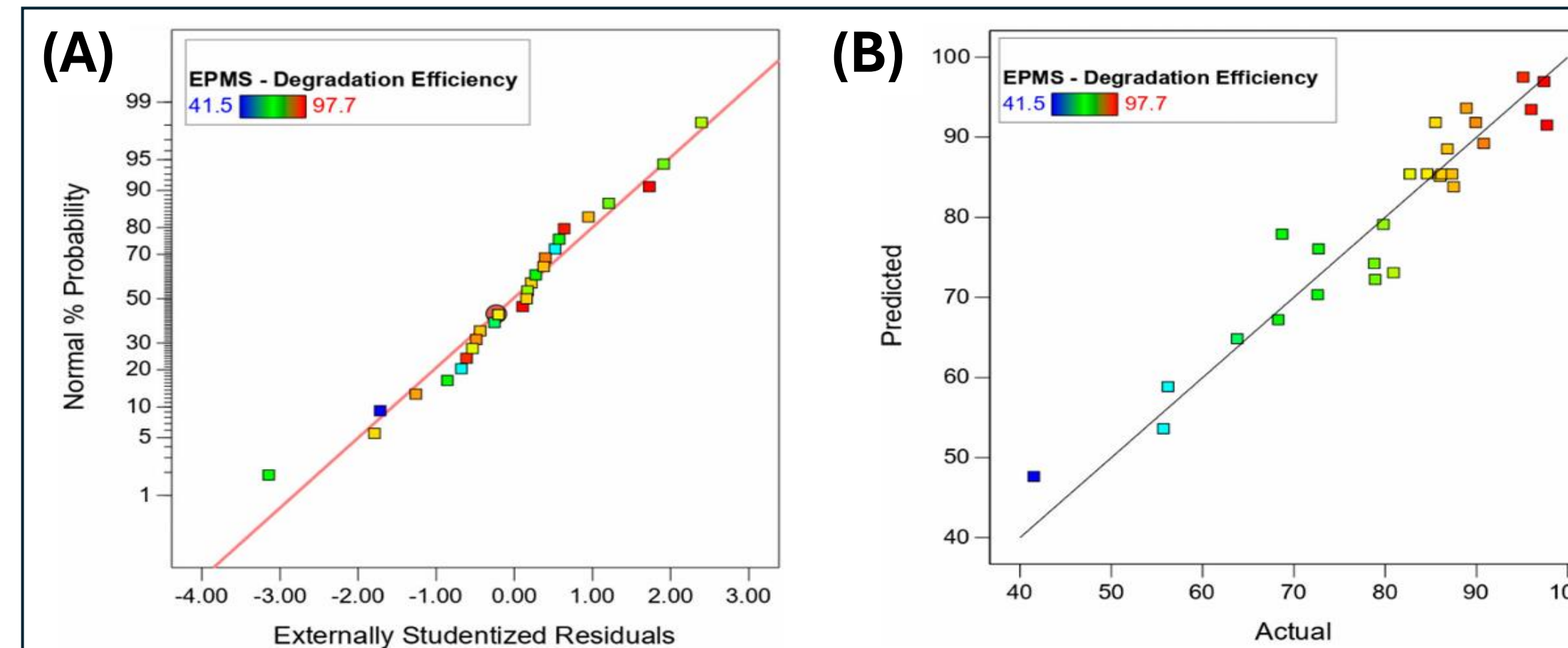


Fig. 5. PMS Progress (A) Normal Probability, and (B) Actual Vs Predicted Values

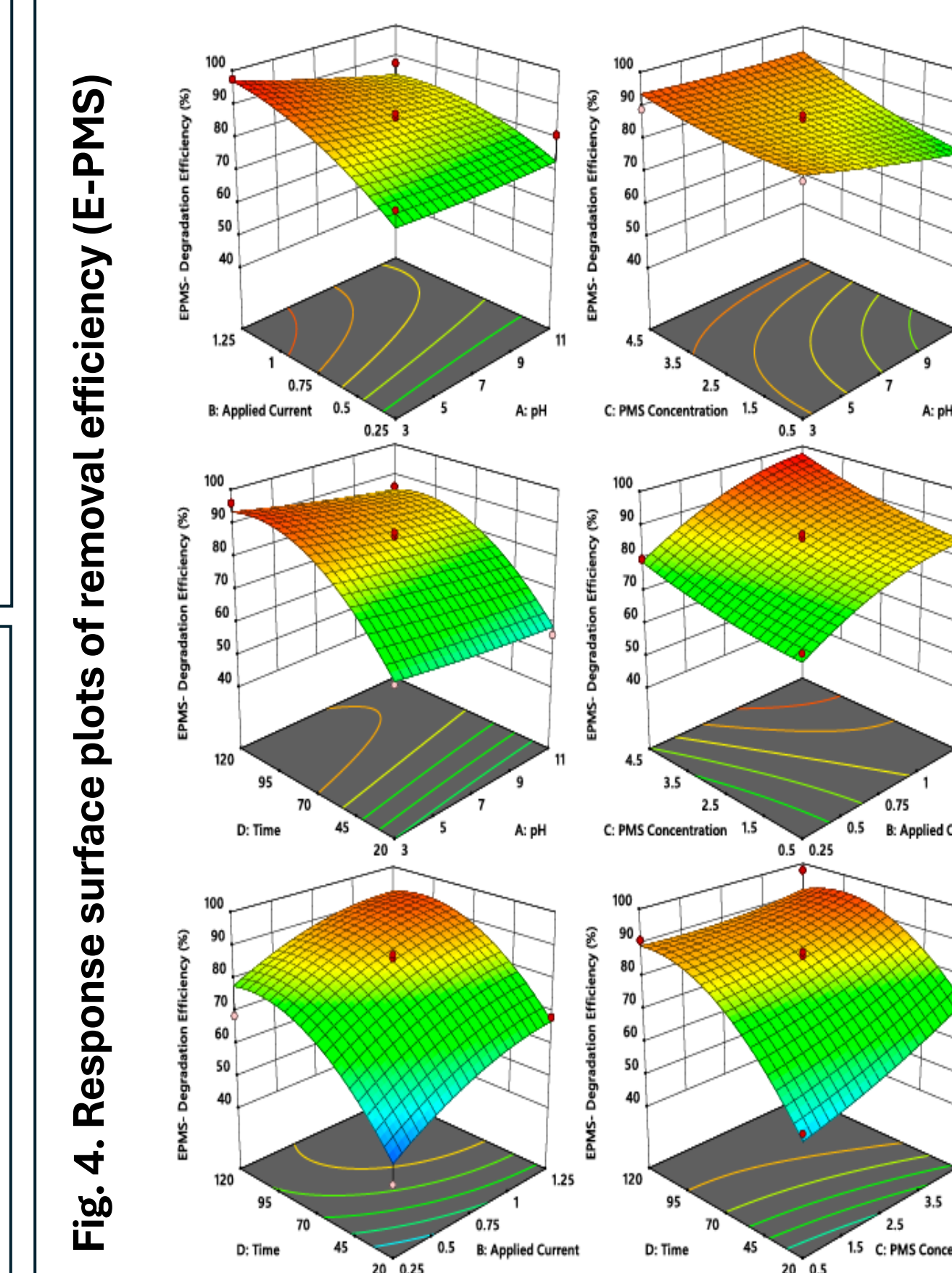


Fig. 4. Response surface plots of removal efficiency (E-PMS)

Tab. 1. Expt. Design Matrix & Results

Run	A pH	B Applied Current	C PMS Conc.	D Time	Removal Efficiency, %	E-PMS Process
1	1 (1)	1 (1)	1 (1)	1 (1)	78.8	
2	1 (1)	1 (1)	1 (1)	1 (1)	80.9	
3	1 (1)	1 (1)	1 (1)	1 (1)	97.4	
4	1 (1)	1 (1)	1 (1)	1 (1)	87.5	
5	1 (1)	1 (1)	1 (1)	1 (1)	55.7	
6	1 (1)	1 (1)	1 (1)	1 (1)	78.9	
7	1 (1)	1 (1)	1 (1)	1 (1)	90.8	
8	1 (1)	1 (1)	1 (1)	1 (1)	97.7	
9	1 (1)	1 (1)	1 (1)	1 (1)	63.8	
10	1 (1)	1 (1)	1 (1)	1 (1)	56.2	
11	1 (1)	1 (1)	1 (1)	1 (1)	96.0	
12	1 (1)	1 (1)	1 (1)	1 (1)	86.0	
13	1 (1)	1 (1)	1 (1)	1 (1)	72.6	
14	1 (1)	1 (1)	1 (1)	1 (1)	84.6	
15	1 (1)	1 (1)	1 (1)	1 (1)	79.8	
16	1 (1)	1 (1)	1 (1)	1 (1)	95.1	
17	1 (1)	1 (1)	1 (1)	1 (1)	72.7	
18	1 (1)	1 (1)	1 (1)	1 (1)	88.9	
19	1 (1)	1 (1)	1 (1)	1 (1)	85.3	
20	1 (1)	1 (1)	1 (1)	1 (1)	41.5	
21	1 (1)	1 (1)	1 (1)	1 (1)	68.3	
22	1 (1)	1 (1)	1 (1)	1 (1)	68.7	
23	1 (1)	1 (1)	1 (1)	1 (1)	81.9	
24	1 (1)	1 (1)	1 (1)	1 (1)	86.2	
25	1 (1)	1 (1)	1 (1)	1 (1)	82.7	
26	1 (1)	1 (1)	1 (1)	1 (1)	87.3	
27	1 (1)	1 (1)	1 (1)	1 (1)		

Conclusion

The dip-coated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/carbon cloth anode demonstrated exceptional performance in electrochemical PMS activation, achieving $\geq 95\%$ removal of Methylene Blue within 60 min under optimized conditions (pH 6, 35°C , 5 mM PMS, 450 rpm) with specific energy consumption $\leq 1 \text{ kWh m}^{-3}$. The synergistic combination of MXene's high conductivity and catalytic terminations with the porous carbon cloth substrate enhanced radical generation ($\text{SO}_4^{\bullet-}$, -OH) and mass transfer, enabling complete dye mineralization without sludge formation. The electrode maintained stable performance over five reuse cycles, highlighting its durability and practical viability. This sustainable EAOP offers a scalable, energy-efficient solution for textile wastewater treatment, aligning with circular economy principles and advancing environmental remediation technologies.

References

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