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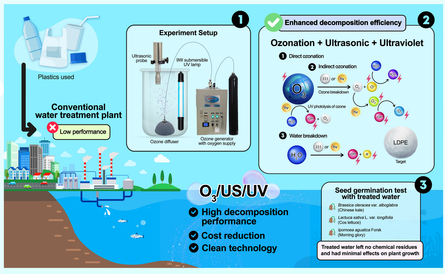
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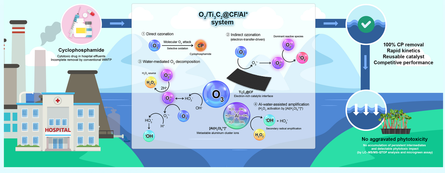
Developing an Environmental-friendly Water Treatment System using Ozonation Technology Combined with Ultrasonic and Catalyst for Emerging Contaminant Removal

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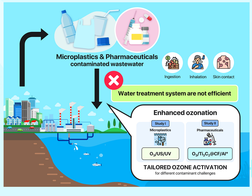
Abstract





Emerging contaminants pose growing challenges to water treatment because their diverse properties require different removal strategies. This research developed two ozone-based processes for two representative contaminants, LDPE microplastics and cyclophosphamide. The O_3/US/UV process enhanced LDPE oxidation through synergistic physical and reactive effects, while the O_3/Ti_3C_2@CF/Al* system accelerated cyclophosphamide degradation through interfacial ozone activation and multiple reactive pathways. Both studies also examined treatment mechanisms and potential environmental impacts, providing complementary approaches for advanced treatment of emerging contaminants.

Introduction



Microplastics and pharmaceutical residues are widely recognized emerging contaminants in aquatic environments. LDPE is highly persistent and resistant to degradation, whereas cyclophosphamide is a biologically active pharmaceutical that is difficult to remove by conventional treatment. Ozonation offers strong oxidative potential, but its efficiency depends on ozone activation and contaminant characteristics. This work therefore explored two tailored strategies using physical-energy activation for LDPE and catalytic ozone activation for cyclophosphamide.

Materials and Methods

LDPE microplastics were treated using individual and combined O_3, US, and UV processes under controlled operating conditions. Treatment performance was evaluated through changes in polymer morphology, chemical structure, oxidation, and surface properties. Reactive-species scavenging, degradation-product analysis, scale-up experiments, and seed germination tests were further conducted to investigate the treatment mechanism and environmental effects.

For cyclophosphamide, Ti_3C_2 MXene was immobilized on carbon fiber and coupled with metastable Al-water to develop the O_3/Ti_3C_2@CF/Al* system. Operating conditions were systematically optimized before evaluating degradation kinetics and treatment performance. Reactive-species scavenging and EPR analyses were used to investigate the oxidation mechanism, followed by transformation-product identification, catalyst reusability, phytotoxicity assessment, and comparison with other advanced treatment processes.

Results and Discussion

Study I — O_3/US/UV for LDPE Microplastics

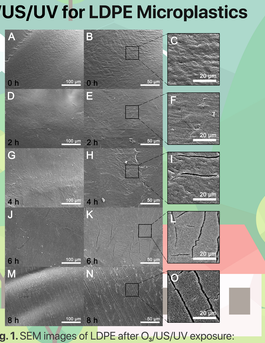


Fig. 1. SEM images of LDPE after O_3/US/UV exposure: (A–C) 0 h, (D–F) 2 h, (G–I) 4 h, (J–L), 6 h, and (M–O) 8 h.

The combined O_3/US/UV process produced greater LDPE decomposition than the individual and dual treatments. Progressive oxidation generated pronounced surface cracks and changes in polymer properties (Fig. 1), while the carbonyl index reached approximately 3.5 after 8 h (Fig. 2).

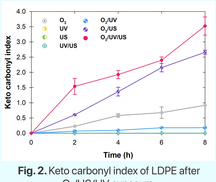


Fig. 2. Keto carbonyl index of LDPE after O_3/US/UV exposure.

Reactive-species experiments showed major contributions from electrons and O_2•$^-$, supporting the synergistic effect of the combined process (Fig. 3). Scale-up experiments further confirmed the advantage of simultaneous O_3/US/UV treatment, while seed germination tests indicated negligible toxicity with a recommended treated-water fraction below 50% for sensitive species.

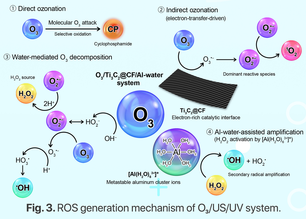


Fig. 3. ROS generation mechanism of O_3/US/UV system.

Study II — O_3/Ti_3C_2@CF/Al* for Cyclophosphamide

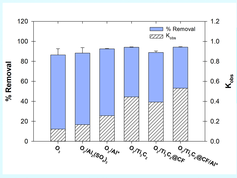


Fig. 4. Comparison of different ozonation configurations.

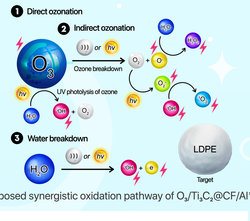


Fig. 5. Proposed synergistic oxidation pathway of O_3/Ti_3C_2@CF/Al* system.

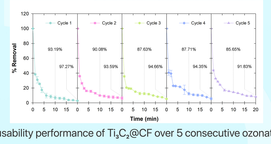


Fig. 6. Reusability performance of Ti_3C_2@CF over 5 consecutive ozonation cycles.

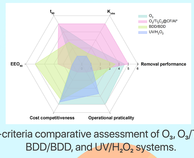


Fig. 7. Multi-criteria comparative assessment of O_3, O_3/Ti_3C_2@CF/Al*, BDD/BDD, and UV/H_2O_2 systems.

The O_3/Ti_3C_2@CF/Al* system markedly accelerated CP degradation, outperforming the individual and partially combined systems (Fig. 4). Mechanistic analyses indicated that interfacial electron transfer enhanced ozone activation through multiple reactive pathways, with an important contribution from O_2•$^-$-related reactions (Fig. 5). The immobilized catalyst maintained more than 90% CP removal after five cycles (Fig. 6). Multi-criteria comparison further showed the fastest degradation kinetics while maintaining competitive overall performance in terms of energy use, cost, removal efficiency, and practical operation (Fig 7.).

Conclusion

Two complementary ozone-activation strategies were developed for contaminants with different treatment challenges. O_3/US/UV enhanced the oxidative decomposition of persistent LDPE microplastics, while O_3/Ti_3C_2@CF/Al* enabled rapid cyclophosphamide degradation through catalytic ozone activation. The findings show that tailoring ozone activation to contaminant characteristics can improve treatment performance while maintaining low environmental impacts under the tested conditions.

Publications

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Pattanateeradetch, A., Sakulthaew, C., Xu, Q., Lin, Y.-T., Frontistis, Z., Mantzavinos, D., & Chokejaroenrat, C. (2026). Immobilized-Ti_3C_2 interfacial ozone activation coupled with metastable Al-water for accelerated cyclophosphamide removal. Journal of Environmental Chemical Engineering, 14(5), 123853.

Acknowledgement

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Thesis Book File