

Development of DBD Plasma-based UV-C Excimer Light Sources for Health and Environmental Applications

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7.1 Conclusion

In this thesis, we have designed, developed and optimized a few DBD plasma-based devices that includes Far UV-C and UV-C excimer light sources which have been applied for various health and environmental applications. The results demonstrate the potential of these excimer sources as viable alternatives to conventional UV sources. To address the current requirement of efficient, easy and cost-effective wastewater treatment methods, this thesis work provides a valuable outcome in terms of Far UV-C excimer source optimization. In Chapter 1, we review the state-of-the-art advancements in DBD-based excimer UV sources, focusing on their electrical-to-optical power efficiency and exploring their diverse applications.

The tasks involved in material synthesis, characterization, and device fabrication require extensive use of specialized equipment and characterization systems, all of which demand a fundamental understanding of their operating principles. In Chapter 2, we have provided a comprehensive explanation of the techniques employed throughout the different stages of the work presented. This chapter covers the fabrication of a DBD-based excimer sources, the synthesis and characterization of metal-oxide nanoparticle catalysts, and a detailed exploration of the synthesis process for a TiO_2 catalyst. To fully characterize the TiO_2 catalyst, we performed an in-depth analysis using XRD, UV-Vis, FE-SEM, HRTEM, and XPS techniques. Additionally, we have outlined the methodology for textile wastewater treatment utilizing both co-axial and planar excimer sources.

In chapter 3, we have shown a successfully developed 222 nm far UV-C excilamp in co-axial and planar configurations. The developed excilamp has been characterized in terms of the electrical input to optical output conversion efficiency and tested for their bacterial inactivation efficiency. High-voltage electrodes have been optimized to reduce lamp heating without external cooling. At a low input power of 31 W and gas pressure of ~ 140 mbar, a very narrow and intense band peaking at 222 nm has been obtained utilizing diffuse discharge with minimized heating. Complete deactivation of two types of microorganisms, i.e., gram-positive (*S. aureus*) and gram-negative (*E. coli*), occurs at the UV dose of 3 mJ/cm^2 and 12 mJ/cm^2 , respectively. The reported UV dose is much lower than the dose reported in the literature for the inactivation of the same microorganisms. This is due to the narrow band emission with FWHM $\sim 1.7 - 1.9 \text{ nm}$ at 222 nm, which resulted in faster deactivation of microorganisms with high efficiency. The developed UV lamp would be the best alternative to conventional mercury-based UV lamps and hence can be utilized in occupied spaces in healthcare settings or indoor environments.

In chapter 4, an advanced XeI^* excimer light source has been developed and used for the degradation of RB5 dye with an A using TiO_2 and H_2O_2 . In the case of XeI^* -excimer/ TiO_2 , 50 mg/L of RB5 was degraded in 40 min when the concentration of TiO_2 loading was 1 g/L at ambient pH. Faster degradation (within 3 min) of RB5 is achieved using the XeI^* -excimer/ H_2O_2 ($\sim 100 \text{ ppm H}_2\text{O}_2$) process in the case of 50 mg/L dye suspension at ambient pH. The mineralization of the dye has also been performed, and more than 95% removal in the COD concentration has been achieved within 40 min of the treatment with XeI^* -excimer/ H_2O_2 . The order of degradation/mineralization is found to be XeI^* -excimer/ $\text{H}_2\text{O}_2 > \text{XeI}^*$ -excimer/ $\text{TiO}_2 > \text{XeI}^*$ -excimer alone. The developed process is environmentally friendly (because no mercury is used) and eliminates the recovery of catalysts from the treated water after degradation. The faster degradation occurs in the alkaline medium (pH 10), making this process more favorable for

wastewater treatment since the textile effluents are alkaline. The results have been compared with existing dye degradation methods, and this environmentally friendly approach is found to be more effective in terms of time taken for degradation and energy yield. The treated water from these separate treatments has been used to germinate radish seeds in the soil. It positively impacts seed germination and root growth compared to untreated dye wastewater. Large-scale textile wastewater treatment is possible with the intended reactor; however, extensive pilot-scale design testing is required to ensure that the reactor is applicable in practice.

In chapter 5, the advantage of the developed DBD-based far UV-C (222 nm) Kr/Cl₂ excilamp was demonstrated for the degradation of complex organic molecules like RB5 dye in DP and in AOP processes using TiO₂/H₂O₂. The RB5 dye is found to have a greater molar absorption coefficient at 222 nm than at 254 nm, and accordingly the designed excilamp performed exceptionally well in degrading RB5 dye. Furthermore, the quantum yield of RB5 dye at excimer-222/H₂O₂ (only 10 ppm H₂O₂) is found 31 times higher as compared to excimer-222/TiO₂, demonstrating the effectiveness of excimer-222/H₂O₂ over other processes. It is found that the degradation rate of RB5 is ~ 27 times faster in the excimer-222/H₂O₂ process, whereas in excimer-222/TiO₂, it is only 4 times faster as compared to excimer-222 DP. The order of degradation/mineralization is found to be excimer-222/H₂O₂ > LPUV/H₂O₂ > excimer-222/TiO₂ > LPUV/TiO₂ > excimer-222 DP > LPUV DP. The E_{EO} of the excimer-222/H₂O₂ process is ~ 500% higher than the excimer-222/TiO₂ process. The developed process is environmentally friendly due to the elimination of mercury usage and effectively obviates the need for catalyst recovery from the treated effluent following degradation. The water resulting from these treatments was tested for its impact on the germination of *Raphanus sativus* seeds. It has demonstrated improved germination percentage, root length, and shoot length compared to untreated wastewater, which confirms its non-toxic nature. With increased operational flexibility and a lower E_{EO} compared to traditional LPUV-based AOPs, this technology holds significant promise for commercial applications. However, for the system to be viable on an industrial scale, further investigation and comprehensive pilot-scale testing are essential. More research is needed to explore the potential of far UV-C excimer sources in sustainable agricultural practices.

In chapter 6, a DDBD plasma reactor and DBD-based KrCl* excilamp were developed to degrade SMX and CBZ from an aqueous solution. Generally, UV/H₂O₂-based AOPs are preferred for the degradation of OMPs. Still, these processes demand the addition of H₂O₂ in the water matrix. In our investigations, the plasma-produced long-lived species, i.e., NO₃⁻ and H₂O₂ are utilized under 222 nm KrCl* excilamp for the enhanced generation of •OH. As a consequence, the faster degradation of the OMPs is achieved. This hybrid process eliminates the burden of removal of residual H₂O₂, and hence termed as green AOP. The degradation of CBZ under DDBD plasma alone requires 210 min for 99.9% degradation, whereas KrCl* excilamp alone requires 40 min of treatment for the same level of degradation. By coupling DDBD plasma with KrCl* excilamp, the 99.9% degradation of CBZ requires only 12 min of treatment. This hybrid approach's required E_{EO} for the OMP degradation is relatively low (73.38 kWh/m³) compared to other methods. If we compare the CBZ and SMX degradation over time under this hybrid approach, CBZ requires 12 min, and SMX requires 8 min of treatment for the complete degradation.

Interestingly, all the other methods have a considerable time difference in degrading two different OMPs with different physical properties. However, this hybrid approach works equally effectively, and the time taken for the degradation of both the OMPs is almost similar. The intermediate and the byproducts are identified using HR-MS, and a degradation pathway was proposed based on the HR-MS data and previous literature. A possible degradation mechanism for plasma + KrCl* excilamp is also proposed.

Overall, this work explored the advancement of excilamp's science and technology and their effective use in different applications related to health and environment.

7.2 Future Scopes

The work presented significantly advances the field of DBD research, offering valuable insights into the development of efficient DBD based Far UV-C and UV-C light excimer sources operating at sub-atmospheric gas pressures. While this research lays a strong foundation, there are still several areas that require further investigation to fully realize the potential of DBD technology for both societal and industrial applications. Future research directions include:

- There is a need for detailed studies on the roles of barrier materials, excitation waveforms, and electrode structures to improve the performance and efficiency of developed DBD systems.
- Further investigation is needed to explore the effective use of low-cost power sources in DBD sources to enhance their economic viability.
- Additional investigation is required to examine the application of modified-XeI* excilamps and 222 nm excilamp on a pilot scale for treating actual textile wastewater and industrial effluents.
- Research is further required on applying modified XeI* excimer sources for sustainable agriculture practices.
- Subsequent investigations should prioritize the examination of degradation byproducts resulting from wastewater treatment using the established techniques.
- Further investigation is required to explore the impact of various other plasma-generated species, apart from NO_3^- and H_2O_2 , on the degradation of OMPs under 222 nm radiation.

Here are some societal and industrial application areas where this research could have a significant impact:

Healthcare Applications: Far UV-C radiation has the potential to be used for disinfection in healthcare settings. It could be integrated into air purification systems, water treatment systems, and surface disinfection devices to reduce the spread of pathogens such as bacteria and viruses, including airborne viruses like SARS-CoV-2.

Public Health and Pandemic Preparedness: In light of recent global pandemics, there is an increased focus on technologies that can mitigate the spread of infectious diseases. Far UV-C radiation could play a vital role in enhancing public health measures and pandemic preparedness strategies by providing efficient and rapid disinfection solutions for various public spaces, including hospitals, schools, public transportation, and high-traffic areas.

Food Safety: Far UV-C radiation can be utilized for enhancing food safety by disinfecting food surfaces, packaging materials, and processing equipment. This can help reduce the risk of foodborne illnesses and improve the shelf life of perishable food items.

Water Treatment: Far UV-C radiation can be employed for the treatment of water sources, including drinking water and wastewater. It offers a chemical-free and environmentally friendly method for disinfection, helping to ensure access to clean and safe water for communities worldwide.

Indoor Air Quality: With increasing concerns about indoor air pollution and its impact on health, far UV-C radiation could be integrated into HVAC (heating, ventilation, and air conditioning) systems to disinfect indoor air and reduce the transmission of airborne pathogens, allergens, and pollutants.

Emerging Technologies: The development of far UV-C radiation sources opens up opportunities for innovation in technology and engineering. Research into novel materials, manufacturing processes, and device designs could lead to the development of more efficient, compact, and cost-effective UV-C light sources for widespread adoption.