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Conclusions and Future Scope

7.1 Conclusions

In the presented thesis work, DBD-based NTP sources were employed to address various biological and chemical indoor air contaminants. The results underscore the potential of these DBD plasma sources as viable alternatives for indoor air purification. This research offers valuable insights into the optimization of DBD plasma sources to meet the demand for efficient, easy, and cost-effective indoor air purification techniques. Chapter 1 provides a comprehensive discussion on indoor air purification, covering pollutant types, their sources, and the limitations of existing technologies. It further explores the promising integration of DBD plasma sources with nanotechnology as an emerging solution for enhancing IAQ. Finally, the chapter highlights the latest advancements in DBD plasma-based technologies for improving IAQ.

The material synthesis, characterization and device fabrication tasks involve a large number of equipment and characterization systems. The use of these instruments requires a basic understanding of working principles. Thus, in Chapter 2, we explained all techniques used during the various stages to carry out the presented work. Additionally, it covers the fabrication of the DBD plasma source, the synthesis of metal-oxide catalysts, and their subsequent diagnostics and characterization. Initially, an explanation of the DBD plasma source's fabrication and characterization is provided. This is followed by a discussion on the synthesis process and characterization of metal-oxide catalysts, detailing their role and performance in the context of the present study. Optical emission spectroscopy used to analyze the emitted plasma, providing insights into the species present and obtaining basic plasma parameters is briefly discussed. Material synthesis, specifically the preparation of TiO_2 NPs as catalysts is described. To fully characterize these catalysts, we employed a range of analytical techniques, including X-ray diffraction (XRD), UV-Vis spectroscopy, field emission scanning electron microscopy (FE-SEM), and X-ray photoelectron spectroscopy (XPS), which have been summarized.

In Chapter 3, we have shown the development of a portable cold-plasma detergent in environment device to efficiently generate negative and positive air ions along with •OH similar to Mother Nature in a coaxial DBD configuration. The device is able to generate plasma detergent ions in the indoor environment without any additional gas and works at atmospheric pressure. A 100 mm device is able to produce active ions with concentrations varying from 300 – 5×10^5 ions/cm^3 and above. It is also able to generate negative ions with an average sustenance time of more than 25 seconds. The device is easily scalable in length, width and ion concentrations. The average consumed power per unit arc length by this device is found to be ~ 0.33 W/cm. The device is quite effective against aerosolized pathogens. It is capable of reducing TBCs and TFCs by more than 99%, *E. coli* bacteria by more than 99.999% and MS2 bacteriophage by more than 99.999% in a shorter operation time (< 60 mins) of the air purifier unit in the indoor environments tested in sizes up to 3 x 2.4 x 2.4 m^3. The enhanced disinfection efficiency can be attributed to the synergistic effect of active air ions and the generated hydroxyl (•OH) radicals.

In Chapter 4, a surface dielectric barrier discharge (SDBD) plasma source combined with a TiO_2 NPs catalyst is shown, and it is effectively used for the decomposition efficiency of VOCs. The removal efficiency of toluene and benzene is reported to be around 99.7% and 74.8%,

respectively, in 60 minutes of continuous operation of the SDBD plasma source. The high energy electrons (HEEs) and reactive species produced by the SDBD plasma are the main driving source for the decomposition process. A bipolar pulsed power source has been employed to generate cold plasma, resulting in intense discharges and the production of energetic electrons within the coaxial SDBD configuration. OES diagnostics reveal that the electron temperature in the plasma discharge ranges from 3 to 6 eV under various applied conditions. The high-energy electrons (HEEs) produced are sufficiently effective in activating the TiO_2 NPs catalyst coated on the outer electrode, thereby generating reactive species that are otherwise activated by UV light. This SDBD system proves to be easily scalable and adaptable for applications such as the degradation of VOCs.

In Chapter 5, we explore and analyze the effects of relative humidity (RH) on the properties of DBD-based atmospheric pressure plasma discharge. We investigated how varying RH influences the production of reactive oxygen species and its subsequent impact on the reduction of airborne total bacteria counts (TBCs) and total fungal counts (TFCs) in indoor environments. Under the same applied voltage, the electric characteristics, i.e., discharge current and power show decreasing trends as RH rises. Water molecules showed a significant impact on the O, N, N_2^* species present in the discharge; as a result, the dissociation of the water causes the concentration of •OH to double under the HH condition. Simultaneously, the amount of O_3 that produced was repressed by half. The XPS analysis of TiO_2 before and after the plasma exposure revealed that the plasma-produced HEEs activate the TiO_2 catalysts for the production of electron-hole pairs and, as a result, the discharge produces different reactive species. The increase in the concentration of on-site produced •OH is also verified by using a chemical probe. The rate of formation of •OH is found to be 9.33×10^{-8} M/s and 17.48×10^{-8} M/s in the LH and HH conditions, respectively. Room disinfection by having TBC and TFC elimination efficiencies of ~ 95.8% and ~ 98.7%, respectively, has been accomplished by the developed DBD-APP source in just 20 minutes of continuous operation.

In Chapter 6, we examined the effectiveness of an indigenously developed non-thermal air plasma source in eradicating ESKAPE pathogens. The study demonstrates that the antimicrobial properties of non-equilibrium cold plasma are primarily due to active air ions and reactive species generated on-site, particularly •OH. These reactive species play a crucial role in disrupting bacterial cell structures and metabolic processes, thereby enhancing the plasma's pathogen-fighting capabilities. In just 60 minutes of indirect treatment, more than 99.9% ESKAPE pathogens inactivation has been achieved. With increase in cold plasma exposure time, inactivation rate increased, possibly due to the prolonged interaction of NE-AACP produced species with the target. Our studies confirmed the DBD discharge can be successfully used in a closed room when without exceeding the safe level of O_3 concentration. The O_3 concentration has been reduced to 0.04 ppm with the application of a catalyst coating that absorbs O_3. The present study also explains the physical and chemical mechanisms underlying bacterial inactivation by non-equilibrium air plasma species. This indirect treatment study of ESKAPE pathogens paves the stage for future research. Moreover, the developed system can be utilised in different indoor settings to reduce the chances of bacterial and viral infections.

In summary, this thesis investigates various DBD plasma sources for the effective removal of diverse biological and chemical contaminants from indoor air. A comprehensive analysis has been conducted on the influence of nanomaterials when combined with NTP methods to achieve optimal performance from the developed DBD plasma sources. The results obtained highlight the significant potential of these plasma sources for improving air quality in enclosed environments, demonstrating their efficacy and versatility in mitigating a wide range of pollutants.

7.2 Future Scopes

The future scope for the present study is promising and multifaceted. The following the few possibilities that can be attempted;

Overall, despite the promising results observed during the presented studies, there are a lot of scopes and dimensions that need to be explored in future. One can investigate the impact of various coating materials, such as $BaTiO_3$, on the production of active air ions and •OH. The investigations can be performed to evaluate the effectiveness of the developed devices for inactivating bacteria and viruses in indoor environments where people are around. A molecular beam mass spectrometer (MBMS) can be utilized to identify various negative and positive ions. The simulation study of the developed device can be performed to determine the electron density and electric field. A better degradation pathway of VOCs can be established using a Gas Phase FTIR Spectroscopy and Gas Chromatography Mass Spectroscopy (GC-MS).

Below are some potential areas where this research could have a significant impact:

- **Advanced Plasma Technologies:** Continued research and development in plasma science and engineering will likely lead to the emergence of more advanced plasma technologies tailored specifically for IAQ control. This includes innovations in plasma sources, reactor designs, and control mechanisms to optimize plasma treatment efficacy and energy efficiency.
- **Integration with IoT and Smart Systems:** Integration of plasma-based air purification systems with Internet of Things (IoT) and smart building systems will enable real-time monitoring, control, and optimization of IAQ parameters. This integration can facilitate automated adjustment of plasma treatment parameters based on changing environmental conditions and occupancy patterns.
- **Multi-pollutant Removal:** Future devices may focus on addressing multiple indoor air pollutants simultaneously, including volatile organic compounds (VOCs), particulate matter, bacteria, viruses, and odors. This requires comprehensive characterization studies to understand the interactions between plasma species and various pollutants, as well as their degradation pathways.
- **Energy Efficiency:** There will likely be a growing emphasis on improving the energy efficiency of plasma-based air purification systems. This may involve the advancement of plasma sources with higher conversion efficiencies, as well as the use of renewable energy sources to power these systems.
- **Miniaturization and Scalability:** Efforts to miniaturize plasma reactors and improve their scalability will enable their deployment in a wide range of indoor environments, including residential, commercial, healthcare, and transportation settings. This involves optimizing reactor geometries, plasma discharge configurations, and electrode materials to achieve compact yet efficient designs.
- **Regulatory Compliance and Standards:** Establishing regulatory frameworks and industry standards for plasma-based air purification systems will be crucial to ensure their safe and effective deployment. This will involve collaboration between researchers, hospitals, industry stakeholders, and regulatory agencies to develop guidelines for system performance, emissions control, and health and safety requirements.

Overall, the future prospects of this research for enhancing indoor air quality are highly promising. The findings pave the way for significant advancements in creating healthier and more sustainable indoor environments, potentially leading to improved public health and well-being through more effective air purification technologies.