

Conclusions and Future Scope

6.1 Conclusion

In this thesis, we designed, developed, and optimized a few DBD plasma-based devices, including Far UV-C and UV-C excimer light sources, which have been applied to milk sterilization studies. The findings highlight the potential of these plasma/UV excimer sources as effective alternatives to the conventional pasteurization process. To meet the current need for an efficient, easy-to-use, and cost-effective milk sterilization method, this work offers significant contributions through the optimization of the Far UV-C excimer source. Chapter 1 provides an overview of the latest advancements in DBD-based excimer UV technologies, emphasizing their electrical-to-optical conversion efficiency and their diverse applications in the food industry.

The design and development of DBD plasma and excimer sources involve the use of specialized equipment and characterization techniques, which require a fundamental understanding of their operating principles. Chapter 2 presents a detailed explanation of the methodologies applied at various stages of the research. This chapter includes the fabrication process of DBD-based excimer sources and their characterization in terms of discharge power and electrical-to-optical conversion efficiency. Furthermore, it describes the methodology used for raw milk treatment employing both Far UV-C and UV-C excimer light sources.

In Chapter 3, we have shown a successfully developed 222 nm far UV-C and 253 nm UV-C excimer lamps. The developed lamps have been evaluated in terms of absolute UV irradiation generation and their electrical input to optical output conversion efficiency. High voltage electrodes have been optimized to reduce lamp heating, without using any external cooling. At optimized parameters of 31.13 W/140 mbar and 25.8 W/200 mbar, the UV reactor demonstrated exceptional performance, producing a very narrow and intense emission band that peaked at 222 nm and 253 nm, respectively. These wavelengths are crucial for effectively targeting and eliminating bacterial contaminants in milk. The diffuse discharge mechanism used in the reactor design minimizes heating, ensuring that the milk is not subjected to excessive thermal stress, thus preserving its physicochemical properties. We found a significantly narrow spectral range (FWHM of 1.7 nm for 222 nm and 1.9 nm for 253 nm) that operates at low pressure with minimal lamp heating ($< 70^{\circ}\text{C}$). The maximum efficiency of $\sim 12.53\%$ and $\sim 17.27\%$ for the UV₂₂₂ and UV₂₅₃ excilamps has been achieved at the gas pressure of 140 mbar and 200 mbar, respectively. The developed far UV-C and UV-C excimer lamp is a safer, more effective alternative to conventional mercury-based UV-C lamps, suitable for use in various applications related to health and environment.

In Chapter 4, we have utilized DBD-based mercury-free KrCl* (222 nm) and XeI* (253 nm) exciplex sources for milk sterilization. From this study, we conclude that DBD-based exciplex UV sources, particularly 222 nm, can be used as a potential solution for milk sterilization to reduce bacterial load without significant or permanent alteration of the physicochemical characteristics of milk. The proposed method is environmentally friendly, efficient at low temperatures, and has minimal effect on the product matrix. The MBRT value of milk increased for more than 5 h, with just 2.5 min of 222 nm treatment. Approximately 2.58 log and 2.11 log decrease in the *E. coli* and *S. aureus* have been achieved after 2.5 minutes of far UV-C (222 nm) treatment of whole milk. The optimized UV dose utilized for the sterilization of whole milk has also been estimated using the chemical actinometry method and found to be 10.9 J/ml at a discharge power of ~ 24.5 W. Our work presents a method for the effective sterilization of milk at low temperatures while also minimizing power usage with a simple reactor design. The obtained results are significant at this

level and show the utility of non-thermal exciplex UV sources to improve milk quality without altering its physicochemical properties.

In another study, our findings suggest that cold plasma technology holds great potential as an effective method for milk sterilization, capable of reducing bacterial load without causing noticeable changes to the physicochemical properties of milk. The technique is environmentally friendly, operates efficiently at low temperatures, and has minimal impact on the product matrix. While most physicochemical parameters remained unaffected by non-thermal plasma treatment, conductivity showed a notable increase, which played a key role in bacterial reduction, as demonstrated by the MBRT test. This study paves the way for low-temperature milk sterilization with minimal energy consumption and a simple system design. Future research could explore continuous treatment systems, conjugate systems, and further enhancements to MBRT improvement for industrial applications. Nonetheless, the current results are promising and highlight the potential of cold plasma to enhance milk quality.

In Chapter 5, a UV reactor has been specifically designed for the continuous sterilization of raw milk, with results indicating that the reactor is an effective method for reducing bacterial load. Importantly, it achieves this without causing significant or lasting alterations to the milk's physicochemical properties. The designed reactor exhibits user-friendly operation, high efficiency at low operational temperature, and no impact on the physicochemical characteristics of milk. The MBRT value of whole milk has increased for more than 5 hours in just four passes of milk from the UV reactor. Approximately 5 log reductions in the *Salmonella typhi* and *S. aureus* was also achieved after three passes of whole milk from the UV reactor. This research presents a simple yet effective reactor design that outlines a low-temperature, power-efficient approach for sterilizing milk. By focusing on minimal energy consumption and maintaining low operational temperatures, the method ensures effective bacterial reduction while preserving the quality and nutritional value of the milk. The straightforward design of the reactor makes it both accessible and practical for potential implementation, offering a sustainable and energy-saving alternative to traditional milk sterilization methods. A very low UV dosage (5 J/ml) is sufficient for total bacterial elimination. Further research on milk shelf life will be required before determining whether UV treatment can be utilized in addition to or instead of pasteurization. However, the results show that this type of UV reactor can effectively improve milk quality without altering the physico-chemical characteristics.

Overall, this thesis presents methods for effective sterilization of milk at low temperatures while also minimizing power usage with simple DBD plasma source designs. By optimizing the UV dose and reactor configuration, the system ensures thorough sterilization while maintaining energy efficiency. A process utilizing a continuous flow of milk in a UV reactor has also been developed. The primary advantage of this method lies in its ability to achieve significant bacterial reduction without exposing the milk to high temperatures, thus preserving its nutritional and sensory qualities. The work carried out can provide an applied solution for enhancing milk safety in dairy operations, offering a balance between effective microbial control and conservation of resources.

6.2 Future Scopes

The work presented significantly advances the field of milk sterilization, 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:

- In-depth research is required to examine the impact of electrode materials, excitation waveforms, and electrode designs on enhancing the performance and efficiency of DBD systems.

- Additional studies should focus on utilizing cost-effective power sources for DBD systems to improve their overall economic feasibility.
- As a first step, we must develop and deploy a solution to reduce bacterial load during the non-cold chain part of the milk value chain.
- Developing continuous cold treatment systems as an alternative to pasteurization or a technique that can be applied with pasteurization will require further investigation (e. g. Vitamin D3).
- Food-grade stainless-steel containers and UV reflectors or coatings that can effectively reflect UV radiation can also be used to further improve the efficacy of excimer UV radiation for milk sterilization.
- Viscosity measurements and correlation studies for different types of milks.

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

1. **Portable UV Sterilization Units:** Developing compact, portable UV-based devices for milk sterilization that can be easily used by farmers in rural or remote areas. These systems would offer a convenient, energy-efficient solution for on-site milk sterilization, eliminating the need for complex infrastructure.
2. **Affordable Solutions for Small-Scale Farms:** Refining DBD plasma and excimer UV technology to design cost-effective sterilization systems tailored to small dairy farms. Simplified designs would help reduce production costs, making the technology accessible to individual farmers.
3. **Off-Grid Power Options:** Incorporating solar-powered or battery-operated UV sterilization units to ensure farmers without reliable electricity can still utilize the technology, allowing for milk sterilization in remote, off-grid locations.
4. **User-Friendly Automated Systems:** Creating automated UV sterilization systems that are easy to operate and require minimal technical expertise. This would enable farmers to incorporate the technology into their daily routines, ensuring better milk safety and quality without the need for specialized training.
5. **Prolonging Milk Shelf Life:** Additional research could focus on using UV-based sterilization to extend milk shelf life, helping to reduce spoilage during transportation and storage. This would benefit farmers by decreasing waste and enhancing the profitability of their milk products.
6. **Field Trials and Local Customization:** Conducting trials in different agricultural settings to fine-tune the UV sterilization process for local milk production conditions, including variations in milk types, storage practices, and environmental factors.
7. **Integration with Milking Equipment:** Investigating the integration of UV sterilization technology directly into milking systems to allow for immediate sterilization post-milking, which would help minimize contamination risks and improve milk quality from the source.

The other important application of such UV sources lies in general sterilization and disinfection, as this spectral range is particularly effective for inactivating a wide range of pathogens. Some of the examples are given below.

1. **Wastewater treatment**, particularly through advanced oxidation processes (AOPs).
2. **Dye degradation** in industrial effluents.
3. **Surface sterilization** of medical equipment, packaging, and food contact surfaces.
4. **Surface modification** of textiles and polymers to enhance dye or coating adhesion.
5. **Active personal air purification**, especially at 222 nm, which is safe for human exposure under controlled conditions.
6. **Prevention of hospital-acquired infections (HAIs)** through airborne and surface disinfection.
7. **Treatment of other temperature sensitive liquid beverages** like Fruit juices to preserve active nutrients.