1
Introduction

The Nobel Prize in Physiology or Medicine in 1903 was awarded to Niels Ryberg Finsen for his significant contributions to the treatment of diseases, particularly lupus vulgaris, through the use of Ultraviolet (UV) radiation. Finsen's pioneering work opened new avenues in medical science [Gøtzsche, 2011].

Ultraviolet is a spectrum of light just below the range visible to the human eye [Sliney, 2016]. Johann Wilhelm Ritter, a German physicist, noticed that invisible rays just beyond the violet end of the visible range darkened silver chloride-soaked paper faster than violet light itself. This led to the discovery of UV radiation in 1801 [Frercks et al., 2009]. He named them "(de-)oxidizing rays" to stress how chemically reactive they were. Soon after, the simpler word "chemical rays" caught on and stayed popular throughout the 19th century, even though some people, like John William Draper, said that this radiation was nothing like light and called it "tithonic rays" [Chang et al., 2005]. The term "chemical rays" was eventually dropped in favor of ultraviolet radiation [Hockberger, 2007]. In 1878, the short wavelength of light was discovered for killing bacteria and thus can be used for sterilization. By 1903, it was known that bands around 250 nm worked best. In 1960, it was proven that ultraviolet light can damage DNA [Witkin, 1966]. Victor Schumann, a German physicist, discovered ultraviolet radiation with wavelengths below 200 nm in 1893. He called it "vacuum ultraviolet" because it is strongly absorbed by the oxygen in the air. UV radiation is categorized into four main spectral regions: Vacuum Ultraviolet (VUV) (100–200 nm), UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm), as depicted in Figure 1.1. The subset of UV-C radiation with wavelengths in the 200-230 nm range is known as Far UV-C [Diffey, 2002].

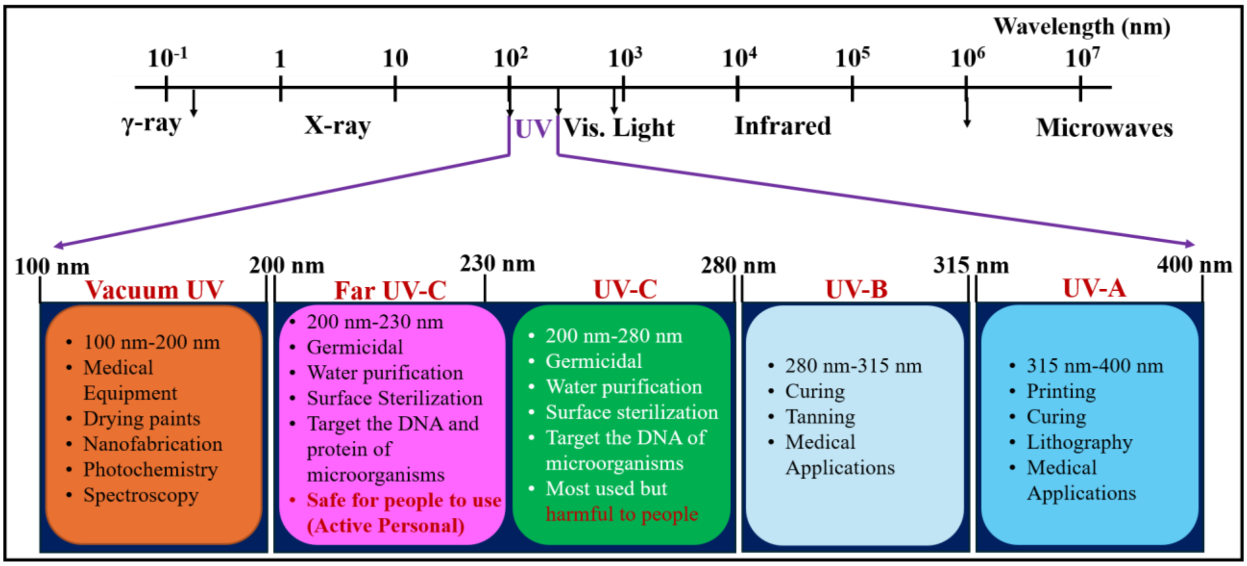


Figure 1.1. Spectrum of electromagnetic light and classification and applications of ultraviolet radiation.

These spectral areas are very specific and have various potential applications, as shown in Figure 1.1. A polymer surface can be smoothed by VUV radiation [Fozza et al., 1999]. VUV light can also be used to deactivate RNA-based viruses [Jalali Milani et al., 2022]. In particular, exposure to UV-B light, the 310 nm narrowband UVB range, is a compelling long-term treatment for many ill skin conditions like psoriasis, vitiligo, eczema, and others [Gambichler et al., 2005]. Certain fungal growths under the toenail can be treated using a specific UV wavelength delivered and safer than traditional systemic drugs. The broad spectral dose of UV-A is quite helpful in printing technologies like UV inkjet applications, UV auto printing, etc. [Scotton et al., 2021]. Furthermore, the UV-C (200-280 nm) is the most lethal range and the best method for disinfection/sterilization known for decades [Keklik et al., 2012] [Trivellin et al., 2021].

From the total spectrum of the Sun, UV rays reaching the earth's surface is 3 %, out of which > 95 % are UV-A radiation. So, for the different UV applications in daily life, scientists have developed artificial UV sources that can generate the specific wavelength of UV light according to the requirement. The development of the different artificial sources is categorized as [Diffey, 2002] [Duarte et al., 2015]:

- **Fluorescent Lamps:** Fluorescent tubes are designed to produce long-wave ultraviolet radiation. These tubes are coated with a special phosphor that absorbs any short ultraviolet radiation produced, ensuring safe and efficient UV emission.
- **Gas Discharge Lamps:** Argon and deuterium arc lamps are categorized as gas discharge lamps. Xenon arc lamps are also gas discharge lamps used in sunlight simulators. Mercury xenon arc lamps and metal halide lamps are other examples of these types of lamps.
- **Mercury Vapor Lamps:** These lamps are gas-discharge lamps that use an electric arc through vaporized mercury to produce ultraviolet rays for therapeutic purposes. There are two types of mercury vapor lamps: air-cooled medium-pressure mercury vapor lamps and water-cooled mercury vapor lamps.
- **Excimer lamp:** Excimer lamps are UV sources developed in the early 2000s and are increasingly used in scientific fields. These have the advantages of high intensity, high efficiency, and operation at various wavelength bands in the vacuum ultraviolet. Different methods like dielectric barrier discharge (DBD), high energy electron beams, microwave discharges, etc., are attempted to develop VUV, Far UV-C, UV-C and UV-B light excimer sources.
- **Ultraviolet LEDs:** LEDs are the most efficient source when the output power required is around 1 W. However, the most dominant and researched LEDs are 395 nm and 365 nm, with an efficiency of around 50%. Other wavelengths of LEDs (particularly UV-C) are under development and require colossal research and testing to validate their sterilization efficiency.

Out of these, the DBD-based methods are found to be the most promising and cost-effective [Lomaev et al., 2012a]. This thesis is focused on the development of high-efficiency DBD-based different UV excimer light sources for health and environmental applications.

The following terms are frequently used in this thesis and are mentioned here in order to enhance the clarity of the text throughout the thesis.

Irradiance (mW/cm^2): Denotes the cumulative radiant power received from all upward directions on a small surface element with an area of (dA), which includes the point being examined divided by the area (dA). A radiometer probe or power meter with the sensor is capable of quantifying the level of irradiance.

The fluence rate (mW/cm^2) is the radiant power that is incident on a very small sphere with a cross-sectional area of dA, divided by the area of dA. The fluence rate accurately represents the amount of UV energy that is delivered to microbial cells within a solution during irradiation.

Fluence (mJ/cm^2) is a measure of the total energy of all the incoming radiation from all directions, divided by the surface area of an infinitely small sphere. Another often employed term for fluence is UV dosage. The product of fluence rate and exposure period determines the total delivered UV energy (UV fluence), which is directly related to the level of microbiological inactivation.

1.1 About Dielectric Barrier Discharge (DBD)

DBD is one of the most typical plasma generation methods. In 1857, W. Siemens reported a novel type of electrical gas-discharge that could generate ozone (O_3) from atmospheric pressure oxygen and proposed it as DBD [J. J. Thompson, 1879]. According to his studies, it consists of two concentric coaxial glass tubes separated by a small gap. DBDs, or barrier discharges, are generated in discharge configurations with at least one dielectric layer sandwiched between the two electrodes [Brandenburg, 2017]. The geometry of DBD is simple, and a common type is shown in Figure 1.2 (a), consisting of two parallel electrodes with a dielectric barrier inserted. The potential difference is applied between two electrodes to create a uniform electric field, and the dielectric barrier is used to prevent sparks and arc formation by limiting the current. The breakdown voltage is determined by the distance between the two electrodes, the gas pressure, and the type of gas. Commonly, DBDs are powered with alternating current (AC) to avoid excessive charge buildup on the dielectric barrier of a DBD reactor, which could lead to the extinction of plasma. The AC amplitude ranges from 1 to 100 kV, and the frequency from 50 Hz to 500 kHz [Ollegott et al., 2020] [Brandenburg, 2018].

DBDs are extremely attractive for industrial applications and can be classified into two primary categories based on the setup configuration, as shown in Figure 1.2. A volume DBD (VDBD) occurs when a dielectric and a discharge gap are present between the electrodes, resulting in the ignition of plasma in the volume between the electrodes [Figure 1.2 (a), (b), (c), and (h)]. The configuration shown in Figure 1.2 (h) has been used for the excimer formation by trapping the rare gas/mixture of rare and halide into it. Surface DBD (SDBD) configurations are defined as "When a dielectric material entirely occupies the space between the electrodes, the plasma is triggered on the surface of the dielectric that is in contact with the gas volume." Streamers arise near the electrodes, where the electric field is strongest due to its significant non-uniformity [Serdyuk et al., 2001]. Figures 1.2 (d) and (e) illustrate the symmetric and asymmetric single-sided DBD geometry. At the same time, the coplanar and symmetric double-sided SDBD are shown in Figure 1.2 (f) and (g). Discharges in these configurations occur when the electric field outside the dielectric reaches a sufficiently high level [Kogelheide et al., 2020] [Pavon et al., 2007].

Under normal atmospheric pressure, these micro discharges usually have a filamentary form that arises from the streamer discharge mechanism. In DBDs, the accumulation of charge on the dielectric material results in an opposing electric field that balances out the electric field generated by the applied alternating current (AC) voltage in the first half of the cycle. This opposing field precludes the occurrence of new streamers at the same location during that half of the cycle. Hence, streamers are dispersed in a manner that follows statistical patterns across the entire discharge gap [Pavon et al., 2007]. A single streamer is usually suppressed within nanoseconds, and a series of short-lived streamers appears for each half-cycle of the applied alternating voltage. With each reversal of polarity, the surface charge that built up during the first half of the cycle, along with the pre-ionized gas, aids in the creation of a streamer at the same location during the next half-wave, resulting in a micro discharge that is confined to a specific area. This phenomenon is referred to as the memory effect [Gu et al., 2021]. The brief duration of the micro discharges results in minimal heating of the surrounding gas, usually only reaching temperatures in the range of a few tens of Kelvin. The electrons acquire a significant portion of the energy contained in the plasma, resulting in ionization, dissociation, and excitation processes that can trigger chemical reactions. Electrons typically have lifetimes on the scale of nanoseconds, but ions have lifetimes that span several microseconds [Träbert, 2002].

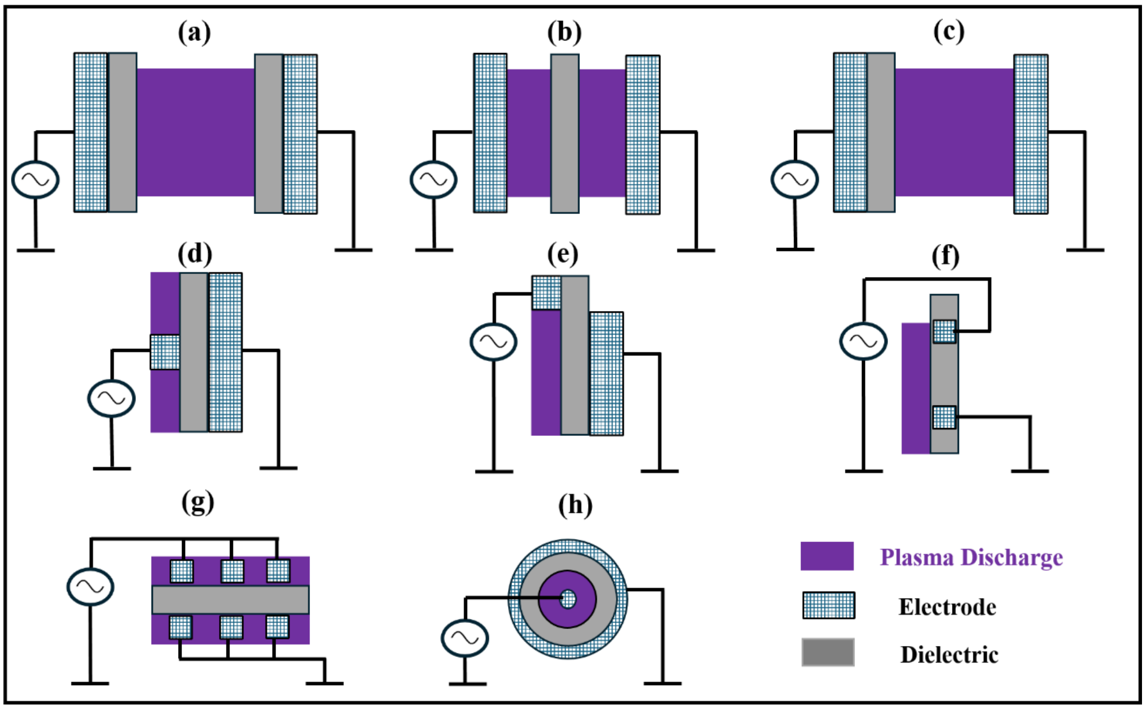


Figure 1.2. Different Configurations of volume and surface DBD geometries: (a) Symmetric Volume DBD with double dielectric barriers, (b) Volume DBD with a floating dielectric barrier, (c) asymmetric Volume DBD, (d) Symmetric single-sided surface DBD, (e) asymmetric surface DBD, (f) coplanar surface DBD, (g) Symmetric double-sided surface DBD (h) cylindrical volume DBD.

Besides the filamentary behavior, the discharge can also operate in a homogenous or diffuse mode. It has been observed that the spatial distribution of micro discharges in DBDs varies enormously according to the applied voltage waveform. Consequently, the discharge can form separate glow discharge domains, symmetrical or cone-shaped blurred discharge areas, etc. Further, the non-homogenous and patterned discharge distribution becomes more homogeneous with increasing applied power. Homogeneity is required to keep peak current densities low, which is believed to be an essential condition for efficient electrical to radiative energy conversion in plasma [Rajasekaran et al., 2010]. The physical parameters of DBDs affect the radiation output; hence, the light conversion efficiency or radiation intensity has been optimized for specific discharge configurations of DBD by external means [Sosnin et al., 2011]. Researchers have increasingly adopted and researched the applications of different DBDs within the past century. The major use was O_3 production for water purification [Qasim et al., 2022] [Tański et al., 2023].

1.1.1 Challenges Associated with Conventional UV Sources

The remarkable capacity of ultraviolet (UV) radiation, specifically UVC (200-280 nm), to disrupt the replication of microorganisms has sparked considerable interest in its potential use in a range of applications, including water and air purification, surface decontamination, blood therapy, milk pasteurization, and sanitization of poultry and agricultural products. Despite the significant potential of UV disinfection, there are two challenges related to present UV sources that conflict with sustainability principles. The presence of a significant quantity of dangerous mercury in conventional UV lamps has raised concerns about their environmental impact. Furthermore, several microorganisms have challenged the inactivation efficiency of currently used sources due to photo-reactivation and their impact on human health.

Currently, UV lamps, primarily mercury-based light sources such as fluorescent lamps, dominate the market, with approximately 1.2 billion UV lamps manufactured annually worldwide. These lamps contain varying quantities of mercury, with Low Pressure (LP) lamps

(254 nm) typically containing 5-50 mg, LP high output lamps containing approximately 26-150 mg, and medium pressure UV lamps containing a substantial amount ranging from 200-400 mg [Mayor-Smith et al., 2021]. Consequently, significant amounts of hazardous waste laden with mercury are generated at the end of their lifespan [John, 1999]. Given the high toxicity of mercury, its environmental impact poses significant concerns. Moreover, mercury-based UV lamps are associated with several issues, including the risk of catastrophic explosions and the subsequent contamination of water and air with toxic mercury, leading to severe health risks. Furthermore, these lamps encounter numerous technical challenges, such as extended start-up times, filament failures, sleeve breakages, dimensional constraints, and lack of reparability, hindering their suitability for wastewater treatment applications [Raposo et al., 2003]. Efforts are going on worldwide to find alternative mercury-free light sources. Very recently, a new generation of lamps are being researched based on excimer radiation that are capable of producing efficient UV to deep UV light radiation [Prakash et al., 2017] [Ahlawat et al., 2024a].

UV photons, when irradiated, can effectively deactivate bacteria by disrupting their genetic nucleic acid structure, whether it be DNA or RNA. However, the globalization of currently available UV sources has been hindered by two types of microbes: (i) those with UV-resistant microorganisms (URMs), (ii) those with effectively repairable microorganisms (ERMs) for nucleic acid lesions post-irradiation. As a result, global environmental protection organizations have regulated the increase in the required UV dose for effective disinfection by UV sources. This, in turn, leads to higher energy consumption and low process efficiency. In addition, regulations typically mandate the use of chemical disinfectants, such as chlorine and O_3, to ensure a lasting impact. However, this contradicts the objective of sustainable UV treatment, which aims to avoid the use of chemical agents.

These mercury-based UV lamps emitting at 254 nm also have issues (they can penetrate skin and eyes and cause skin cancer and cataracts) when used in active personal mode. Thus, their applicability is restricted to the field of active personal air and surface sterilization, as these sources are incompatible with working environments [Pfeifer et al., 2012].

Recently, an exciting theory came into existence about the UV-C band of spectrum (200-230 nm) known as ‘Far UV-C’ and is found to be safe to expose in occupied space while used in controlled dosage as it cannot penetrate the human skin (get absorbed in the dead skin cells) and eyes (absorbed at the tear layer of eyes), as shown in Figure 1.3 [Yoshiyama et al., 2023]. These findings opened up many opportunities to use in engaged areas like hospitals or public spaces to prevent airborne infections and antimicrobial-resistant diseases [Buonanno et al., 2017b]. Now efforts are underway to develop appropriate active personal Far UV-C light sources with high bactericidal efficiency. So, creating low-cost, handy UV sources for medical applications, industrial wastewater treatment applications, and air and surface sterilization is the need of the hour. Developing such new-generation UV lamps with optimum operating parameters to meet these critical requirements is a challenge that would be attractive for both commercial and public sectors.

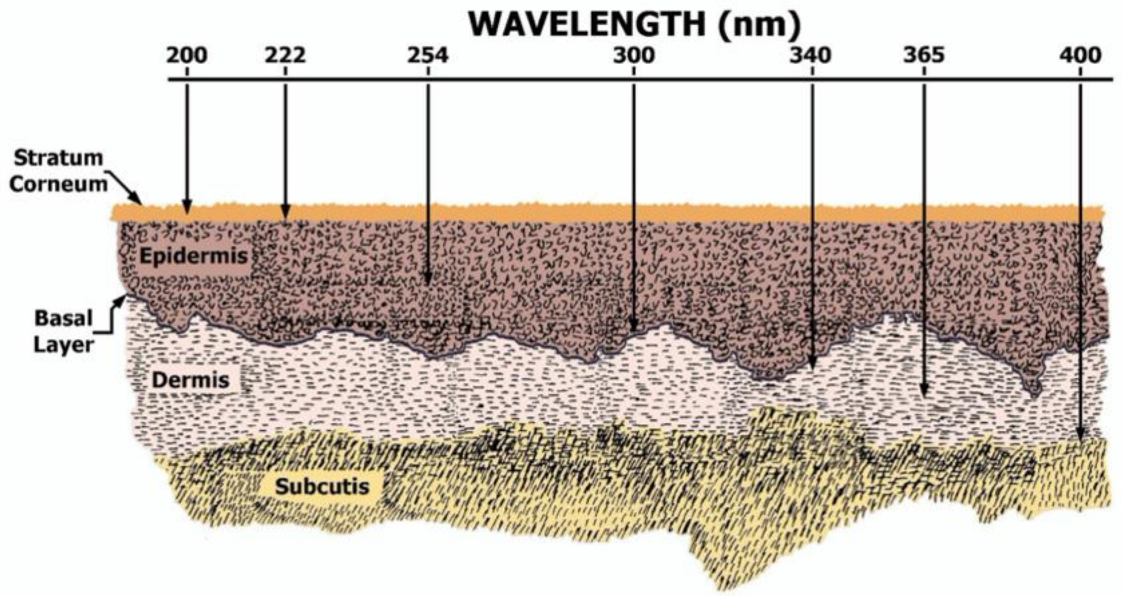


Figure 1.3: The penetration of different UV radiation wavelengths into the human skin. (Figure courtesy David H. Sliney)

1.2 Light Generation with DBDs and Mechanism of Excimer Formation

In most cases, the excimer lamp's geometry is typically coaxial in DBD configuration; there are variations in their sizes, gas species, and power sources [Brandenburg, 2017]. Typical geometries used for the planar light panels and cylindrical lamps are shown in Figure 1.4 (a, b) and (c), respectively. The quartz container also functions as a dielectric barrier. The outside or front electrodes consist of metallic wire meshes, perforated metallic films, or transparent metallic layers. The rear electrode can function as a mirror. Plasma emits either UV or VUV photons, which can be utilized for various applications such as surface sterilization, water purification, skin curing, etc., using excimer lamps [von Woedtke et al., 2022]. Alternatively, these photons can be transformed into visible light by exciting phosphors coated on the vessel's inner surface. Coplanar electrodes can be used to make flat light panels [Figure 1.4 (b)]. Thick film printing is used to create these lights.

In the last one decade or so, powerful and efficient excimer light sources have been developed, with several applications in industrial UV-induced processes. Researchers realized that the DBDs operated at high-pressure rare gases or rare gas/halogen mixtures, the discharge acts as an intensive source of ultraviolet (UV) or Vacuum ultraviolet (VUV) radiation due to the formation of excimer molecules in the discharge volume.

The production of light from DBDs relies on the formation of plasma within specific gas combinations that are enclosed in quartz containers within the discharge gap. The gas mixture typically includes a buffer gas, a combination of noble gases, to facilitate a low ignition voltage [Nijdam et al., 2022].

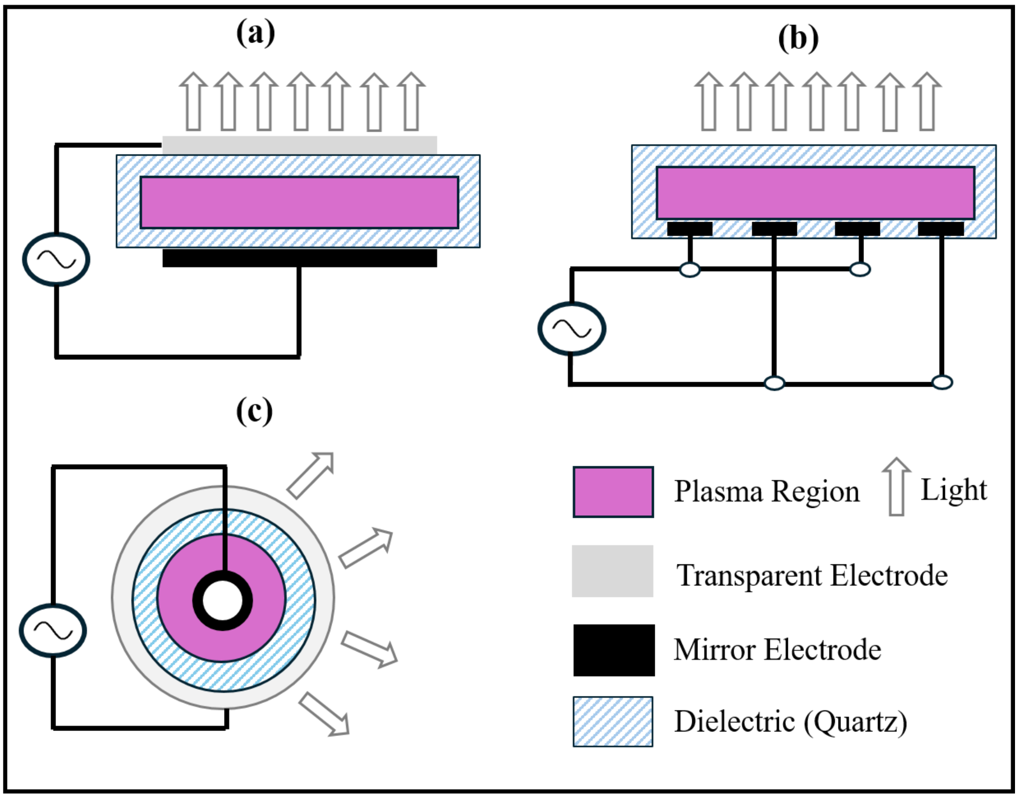


Figure 1.4. Basic configurations of DBDs used for the generation of light.

The DBD-based excimers are the best alternative for generating UV/VUV radiation either with rare gases or a rare gas mixture of halogens [Sosnin et al., 2006] [Lomaev et al., 2003a]. It is well known that the excimers, which are unstable excited molecular complexes, are generated in several ways, e.g., by DBDs, high-energy electron beams, x-rays, synchrotron radiations, protons, heavy ions, and microwave discharges [Furusawa et al., 1995; Kogelschatz, 2004; Ulrich et al., 2009]. DBD plasmas are used as effective sources of the excited dimmer, which terminates in the unbound or weakly bound metastable states and leads to the effective generation of VUV/UV or visible light radiation. This is one of the most proficient ways to produce the necessary precursor for the formation of excimers because DBDs can produce highly energetic electrons and excited dimmers at high pressures. Furthermore, the DBD plasmas have potential adaptability for industrial applications because of their simplicity or geometric freedom, high efficiency, low cost, etc. [Bogaerts et al., 2002].

1.2.1 Mechanism of Excimer and Exciplex Formation:

Irrespective of their excitation method, excimer and exciplex molecules undergo the identical energy relaxation process across their electronic states within the medium. The presence of ionized and excited states, which are connected to each other by multiple interactions of potential energy curves, results in the relaxation of the gas medium through a non-radiative sequential population of excited states. The transition from the lower excited states of the excimer and exciplex molecules to the ground states is radiative. The energy difference between the lower excited state and the ground state is significant. This phenomenon can be attributed to the efficient conversion of energy from gas to electromagnetic radiation, as well as the occurrence of specific transitions in the emission spectrum within the ultraviolet (UV) and vacuum ultraviolet (VUV) ranges of the electromagnetic spectrum [Sosnin et al., 2006]. The B-X transition has the highest intensity among rare gas halogen exciplex molecules. Additionally, there are weaker transitions such as D-X, D-A, and C-A and emission bands related to halogen dimer molecules [Zhang et al., 1998], shown in Figure 1.5 (a).

The exciplex can be formed by two reactions: the first is a three-body ion-ion recombination reaction, and the second is a harpoon reaction, i.e., a two-body reaction [Klenovskii et al., 2013a]. When the high voltage is supplied to the DBD-based excimer/exciplex sources, the plasma formation takes place below atmospheric pressure, triggering the generation of highly energetic electrons, and due to these, the excitation and ionization of both the gases (e.g., Kr and Cl_2) take place. In this example, the cations of krypton and anions of chlorine gas get involved in a three-body recombination reaction with an atom or molecule of active species or buffer gas (M) and form the excited complex (KrCl*) as,

$$\mathrm{Kr^+ + \ Cl^- + M \ \rightarrow \ KrCl^* +} M \tag{1.1}$$

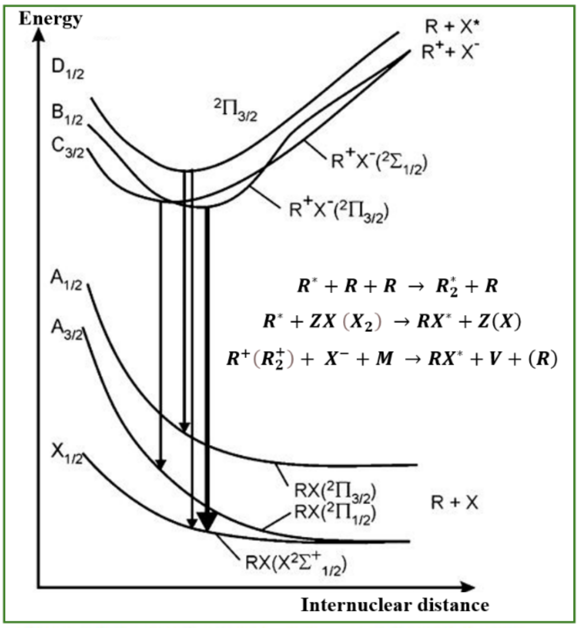
A harpooning reaction can form an excited complex in which the excited krypton species transfers its loosely bound electron to the chlorine molecule to form an electronically excited state of KrCl*.

$$\mathrm{Kr^* + Cl_2 \ \rightarrow \ KrCl^* + \ Cl} \tag{1.2}$$

The KrCl* exciplex molecule is considered to have a short lifetime in its excited state. It de-excites, followed by the rapid decomposition in the nanosecond timescale, and emits photons having a wavelength of 222 nm as

$$\mathrm{KrCl^* \ \rightarrow Kr + Cl +} hv \ (222 \text{ nm}) \tag{1.3}$$

The three-body ion-ion recombination reaction generally requires high gas pressure (above 150 mbar), whereas the two-body reaction, i.e., harpoon reaction, happens at low gas pressure [Klenovskii et al., 2013a].



Rare gas atom (R)	Halogen atom (x)	Different transition wavelength of RX* molecule (nm)			
		$D_{1/2} \rightarrow X_{1/2}$	$B_{1/2} \rightarrow X_{1/2}$ (η)	$C_{3/2} \rightarrow A_{3/2}$	$D_{1/2} \rightarrow A_{1/2}$
Ne	F	106	108 (0.43)	110	111
Ar	F	185	193 (0.35)	203	204
Ar	Cl		175 (0.48)		195
Ar	Br		165	172	183
Kr	F	220	248 (0.28)	275	272
Kr	Cl	200	222 (0.31)	240	235
Kr	Br		207 (0.33)	222	228
Kr	I		190 (0.37)	195	225
Xe	F	264	351 (0.24)	460	410
Xe	Cl	236	308 (0.27)	345	340
Xe	Br	221	282 (0.29)	300	325
Xe	I	203	253 (0.37)	265	320

Figure 1.5. (a) Potential energy diagram of rare gas halogen exciplex molecules XeI*, KrCl* and KrI* and the corresponding intense radiative transitions, (b) wavelengths of the principal radiative transitions in exciplex molecules and the theoretical maximum efficiency of B-X transition [He et al., 1998].

The UV/VUV radiation dynamics from DBD-driven excilamp were experimentally studied for the first time by Lomaev et al. [Lomaev et al., 2003b]. In earlier days, the disadvantage of DBDs was that the UV radiation generation was characterized only by 4 -10% electrical to optical convergence efficiency. However, Vollkommer and Hitzhschke [Pascal, 1997] solved certain fundamental hindrances and improved efficiency but the heating of the excilamp remains a challenge. The new configuration led to the development of a UV-C source by QuantaDose, USA, in 2020, as shown in Figure 1.4, with an output power of 2W. Such alternative VUV/UV sources are based on the electrical gas discharge in DBD configuration, and several wavelengths can be generated using mixtures of noble gases and petite halides, as shown in Figure 1.5 (b) [Zhang et al., 1996a].

The prominent feature of such sources is their stability in the excited state without self-absorption in the ground state and the absence of mercury inside the UV/VUV lamps. Also, their spectral characteristics can be tuned by regulating supplied voltage, gas pressure, and frequencies. They are more suitable for immediate usage in disinfection/sterilization due to instantaneous start-up [Masoud et al., 2013]. DBD-based excimer lamps are also sometimes called electrodeless lamps since, in many cases, no electrode is in direct contact with the gases. This results in a long lifespan of lamps because metal sputtering and electrode erosion do not occur on the inner walls of the quartz in this situation [Zhang et al., 2000] [Oppenlander, 2005]. Also, excimer/exciplex sources provide a very intense B-X transition in the case of rare gas only. Still, for a mixture of rare and halide gases, some weak transition also occurs along with intense B-X transitions in the UV/VUV range, allowing them to have a high conversion efficiency of the electrical input to the optical output. Studies have shown that for the case of Kr/Cl_2 exciplex, a very intense B-X transition appears at 222 nm with some weak transitions, i.e., D-X, B-A, and C-A at 200 nm, 235 nm, and 240 nm, respectively [Lomaev et al., 2002a]. By adjusting operational parameters like input power, gas pressure, and discharge gap, it is possible to adjust the contribution from different electron transition bands and their bandwidths [Rahmani et al., 2009b].

1.2.2 Electrical to Optical Conversion Efficiency of Excilamps

Electrical to optical conversion efficiency refers to the ratio of the optical (light) energy output to the electrical energy input. It measures how efficiently an excilamp converts electrical power into UV light or other desired wavelengths.

J.-Y. Zhang and I. W. Boyd [Zhang et al., 2000] reported that a cylindrical coaxial lamp utilizing filamentary discharges and excited by radio frequency (RF) power source from 3.5 kV to 10 kV having a frequency range of 125-375 kHz gives a maximum efficiency of 6% at an input power of 30 W at a gas pressure of 600 mbar. In this case, heating of the gas mixture/quartz became a problem at higher gas pressure with filamentary discharges. So, to control the heating of the gas mixture, they used a separate water-cooling system by isolating the inner electrode. Zhuang et al. [Zhuang et al., 2010] have compared the efficiency with different power sources, i.e., sinusoidal (peak voltage 7.93-12.8 kV, 100 to 500 W power setting), pulsed (0.75 μs pulse width, 90 kHz frequency, 5.2 to 7 kV, 100 – 500 W power setting) and rectangular (20 μs period, frequency 50 kHz) and reported that the maximum efficiency of a coaxial excimer lamp having filamentary discharge is 9.2% at 200 W when operated with a pulsed source and a total gas pressure of 200 mbar. With a pulsed power supply and a Kr/Cl_2 mixture of 100:1, Panchenko et al. [Panchenko et al., 2008] reported a maximum efficiency of 10% with homogeneous diffuse discharge at a total gas pressure of 150-200 torr and breakdown voltage of 20 kV. The reported input powers in the above studies were very high, limiting the findings to use in practical applications. Hence, a device with low input and high output power efficiency is the requirement for practical applications. Furthermore, high irradiation intensity is the requirement for high disinfection efficiency.

Rahmani et al. [Rahmani et al., 2009a] reported a maximum electrical to optical power conversion efficiency of the order of 4.5% despite having high UV irradiation of 36 mW/cm^2. In fact, UV irradiation is not the only controlling factor for high electrical-to-optical conversion efficiency. It can depend on pulse shape, input power, gas pressure, gas/discharge gap, etc., for example, bipolar pulse power sources are best suited for Kr/Cl_2 exciplex lamps [Lomaev et al., 2012b]. Narrow and intense bands are considered highly preferable for the Kr/Cl_2 exciplex sources at 222 nm wavelength. Another group [Brau et al., 1975] reported that at high temperatures, the B-X transition band was broader, and they inferred that the temperature and pressure of the gas affect the FWHM of the transition band. Therefore, designing, developing, and optimizing an exciplex of 222 nm with Far UV-C light having high efficiency, diffused discharge, and narrow band emission at low pressure with less heating is a critical need.

1.3 Potential Applications of the Excimer Sources

There are various uses of Excimer UV-C and Far UV-C sources in the health, environment, textile, and food and beverages industries, as shown in Figure 1.6, as they can efficiently disinfect surfaces and air without chemical agents [Lv et al., 2023; Palma et al., 2022; Song et al., 2023; Tchonkouang et al., 2023].

This thesis work is focused on the design, development and optimization of cylindrical and planar excilamps emitting different wavelengths in the range of ultraviolet light regions for health and environment applications. The main aim is to utilize the developed sources to analyze bacterial disinfection efficiency on different surfaces and in aqueous suspension as well as to analyze their effectiveness in industrial wastewater treatment containing dyes and various organic contaminants.

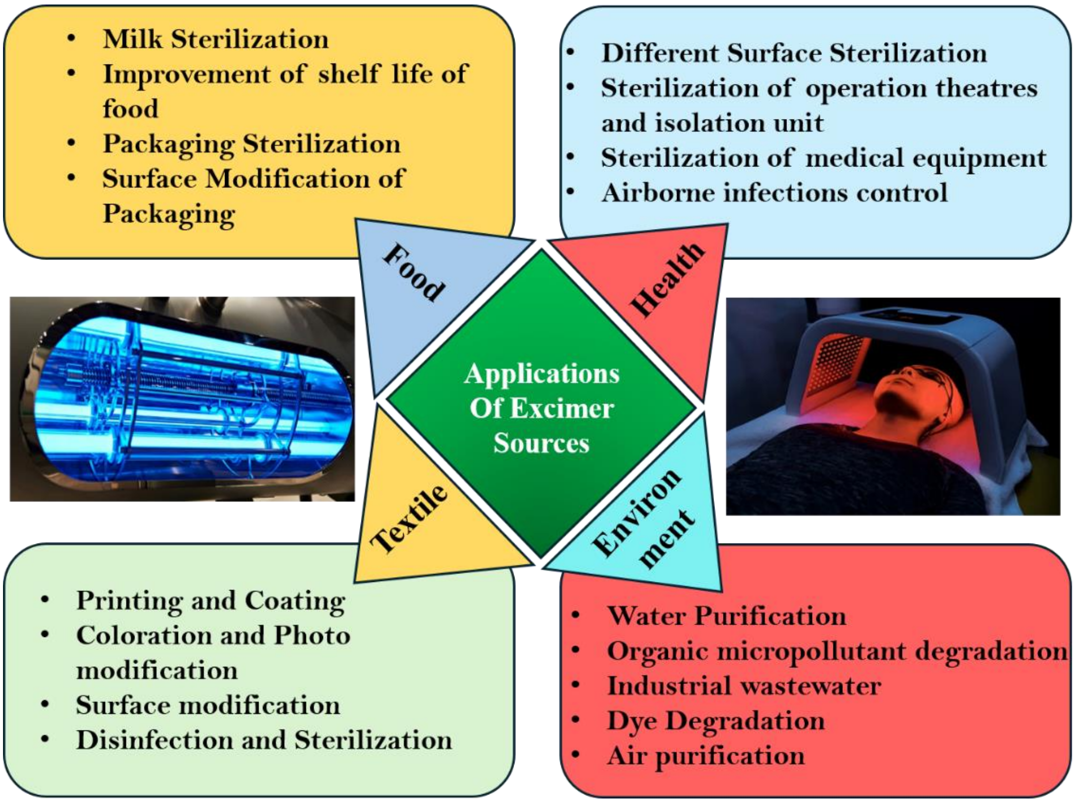


Figure 1.6. Various applications of excimer light sources in health, environment, textile, and food sectors.

1.3.1. Health Applications

Most recently, the DBD technology opened possible emerging novel applications in biology and the medical field [Braný et al., 2020; Choi et al., 2022; Laroussi, 2018]. Figure 1.7 (a) illustrates the dissociation energy of different chemical bonds and the maximum emission wavelengths of narrow bands of excimer and exciplex molecules [Buonanno et al., 2024].

Excilamps can be advantageous in some practical scenarios as they can emit narrow-band UV light that aligns with the absorption spectrum of the irradiated materials [Xu et al., 2023a]. This alignment enhances the effectiveness of the photochemical process. There are cases where the property of excilamps spectra has been utilized in the advanced solidification of polymer film and coatings in the printing sector, namely by applying XeCl* excilamps. XeCl* excilamps can indeed be used for health applications, especially in dermatology and phototherapy [Sosnin et al., 2006] [Alyoussef, 2023].

Furthermore, different radiation wavelengths are responsible for the various biological effects, such as photo-inactivation of the functional ability at $\lambda < 300$ nm [Ma et al., 2021] [Fukutoku et al., 2024]. Figure 1.7 (b) illustrates the absorption curve of the nucleic acid (DNA) and protein of the bacteria and viruses concerning different UV wavelengths. The mode of bacteria and viruses' inactivation is different at 254 nm and 222 nm. On one hand, the UV light at 254 nm is primarily absorbed by the nucleic acids (DNA or RNA) in the microorganism's cells. When absorbed, UV photons cause the formation of covalent bonds between adjacent thymine or cytosine bases within the DNA or RNA molecule, leading to the formation of thymine dimers or cytosine dimers, respectively. The formation of these dimers disrupts the typical structure of the genetic material, interfering with replication and transcription processes essential for the microorganism's survival and reproduction. As a result of DNA or RNA damage, the microorganism becomes unable to replicate or express essential genes, leading to its inactivation and inability to cause infections or reproduce in the environment [Wang et al., 2019a] [Kang et al., 2019].

On the other hand, the UV light at 222 nm is absorbed by the peptide bonds present in the proteins of microorganisms. Unlike UV light at 254 nm, it does not directly damage microorganisms' genetic material (DNA or RNA). When absorbed by the peptide bonds, UV photons cause the formation of cross-links within the protein structure, leading to the denaturation and fragmentation of proteins. The denaturation and fragmentation of proteins disrupt essential cellular processes, such as enzymatic reactions, protein synthesis, and membrane integrity, ultimately leading to cellular dysfunction and inactivation. Without functional proteins and cellular processes, the microorganism cannot maintain its structural and metabolic integrity, resulting in its inactivation and inability to replicate or cause infections [Naito et al., 2022] [Lorenzo-Leal et al., 2023].

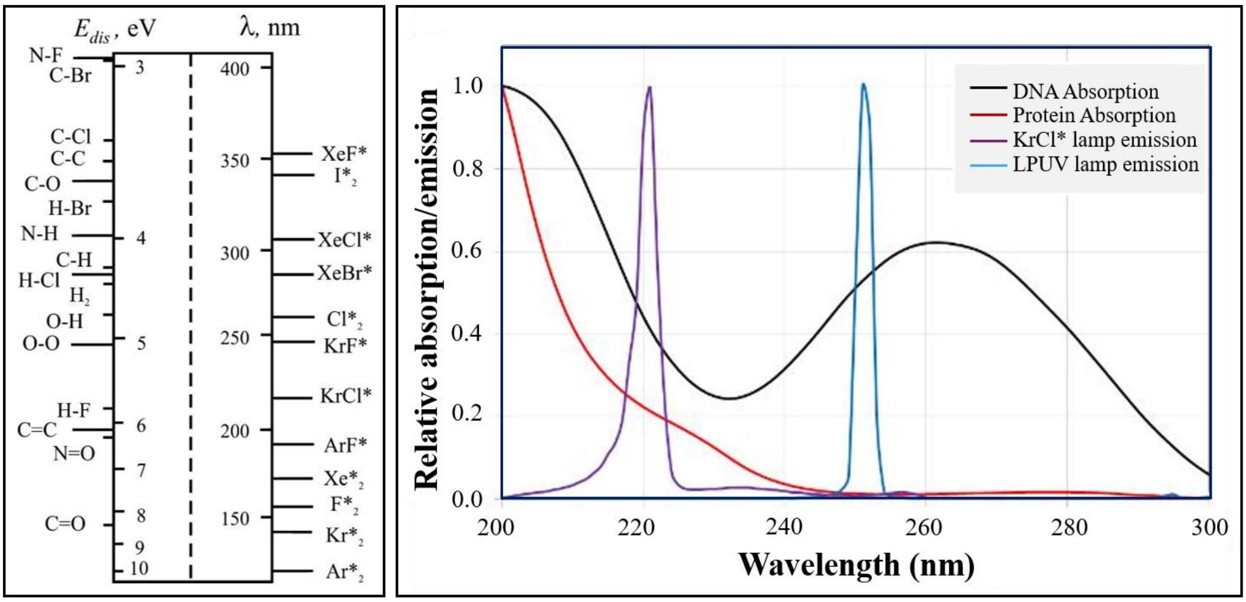


Figure 1.7. Emission spectra of KrCl* and LPUV lamp at DNA and protein absorption curves.

As per the literature, an excimer lamp of far UV-C (222 nm) light provides a more efficient way of disinfecting harmful microorganisms by adding safety to mammalian skin and eyes due to its less penetrating power and more absorbance in biological materials [Id et al., 2020]. Eadie et al. [Eadie et al., 2021] used Monte Carlo simulations to model human skin and determine the appropriate far UV-C exposure limit for skin and eyes. A filtered Krypton-Chloride (KrCl) far-UV-C system with peak emission at 222 nm was used to subject a Fitzpatrick Skin Type II person to significant radiant exposures on their inner forearms. At 1500 mJ/cm^2, there were no discernible skin alterations, but at 6000 mJ/cm^2, there was an instantaneous appearance of skin yellowing that disappeared within 24 h. With exposures up to 18000 mJ/cm^2, no erythema was noticed. These findings and computer modeling using Monte Carlo Radiative Transfer indicated that far UV-C devices are safe on human skin when longer ultraviolet wavelengths are filtered out. The disinfection efficiency of a UV source is defined as UV fluence (mJ/cm^2), which depends on the UV exposure time, irradiation, and the medium of bacterial inactivation [Ahlawat et al., 2023] [Ahlawat et al., 2022].

Narita et al. [Narita et al., 2020] evaluated the effectiveness of disinfection at 222 nm and 254 nm on several bacteria and fungi in aqueous media and made a comparative analysis. According to them, the 222 nm excimer light had a higher disinfection efficacy for bacteria than conventional 254 nm, although the 254 nm lamp performed better against fungi. When 0.5 ml of solution for each sample was used, the UV dose by the 222 nm excimer lamp for complete deactivation of *S. aureus* and *E. coli* was reported to be 12 mJ/cm^2 and 24 mJ/cm^2, respectively. High-concentrated (10^7 CFU/ml) gram-positive (*S. aureus*) bacteria inactivate more slowly than similar concentrations of gram-negative (*E. coli*) bacteria when exposed to a UV dose of 351 mJ/cm^2 for 180 s [Matafonova et al., 2008]. They performed bacterial inactivation in an aqueous medium. They also noticed that the same bacteria's dose requirements drastically differ under identical experimental conditions. There exist other factors other than UV dose that can affect bacterial inactivation. The efficiency of bacterial inactivation can depend on band emission characteristics of the UV source, i.e., narrower or broader, and the type of discharge, i.e., filamentary or diffused, because these factors significantly affect the electrical to the optical conversion efficiency of the excimer sources and needs to be researched further.

1.3.2 Environmental Applications

Micro-pollutants are newly identified contaminants of concern in the environment and come from various sources, such as natural occurrences and human actions. Aquatic organic micro-pollutants (OMPs) are a global concern because they are found extensively in water systems [Barcellos et al., 2022]. Between 2010 and 2015, the European market recorded almost 145,000 new compounds, a significant number of which eventually ended up in water bodies. Despite the typical methods used to treat wastewater, most harmful substances are not effectively eliminated or converted, resulting in their build-up in aquatic ecosystems and potential negative impacts on marine life and human health [Tran et al., 2023].

Micro-pollutants are a diverse category of pollutants distinguished by small size and frequently intense ecological consequences [Yang et al., 2022]. They can arise from numerous sources, including industrial, agricultural, and residential activities [Pronk et al., 2024]. Due to the excretion of OMPs through bodily waste and the improper disposal of undesired or expired medications, a significant amount of these pollutants ends up in sewage. Consequently, the disposal of untreated or inadequately treated wastewater is recognized as a primary contributor to the presence of these pollutants in environmental systems [Eggen et al., 2014]. Figure 1.8 shows the various sources of origin for micro-pollutants, affecting parameters, removal technologies, and their interaction mechanisms.

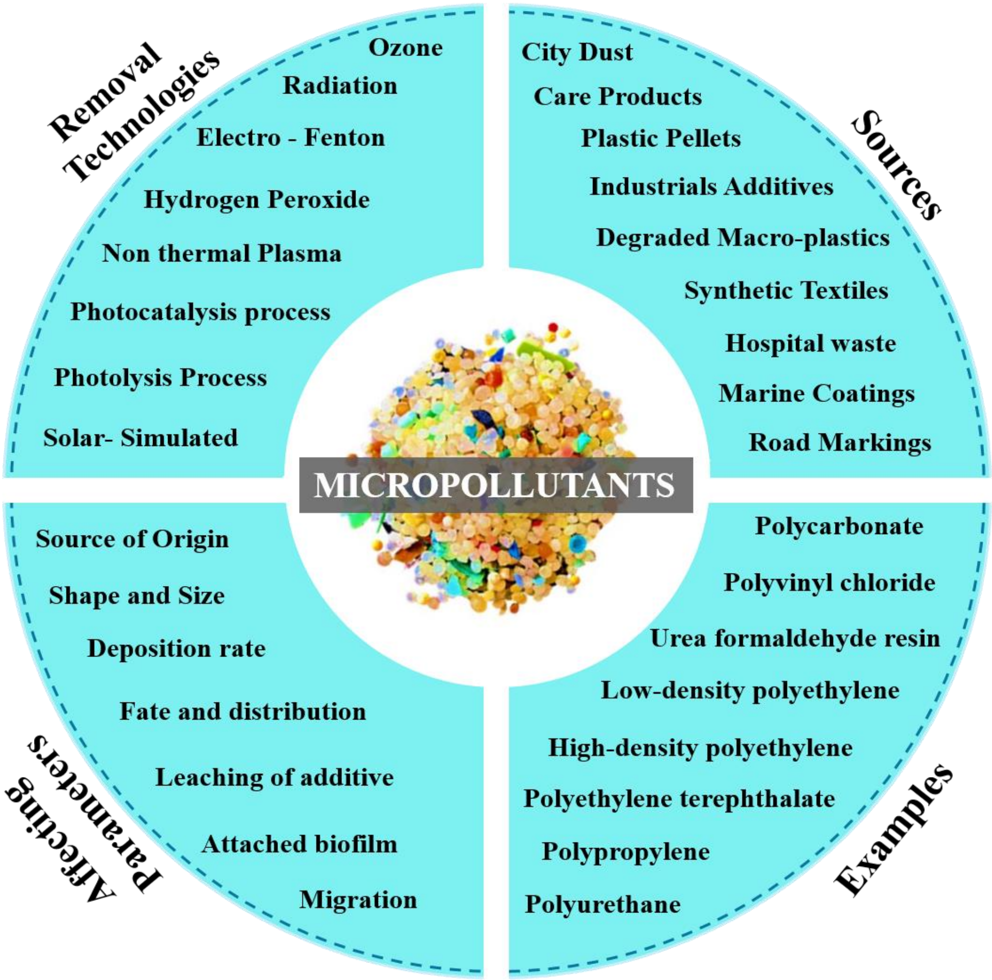


Figure 1.8. The sources, parameters, and removal technologies of different micro-pollutants found in the environment.

Currently, significant attention is devoted to the OMPs present in surface water, as they are considered to be the primary origin of emerging micro-pollutants (EMPs) detected in the water [Pisharody et al., 2022] [Payne et al., 2022]. WWTPs may release either treated or untreated wastewater effluent straight into aquatic bodies, such as rivers, lakes, and reservoirs. Emitted OMPs can either settle on sediments or be transported to different locations through hydrological processes [Xi et al., 2022]. The decomposition of these compounds in surface water, both through chemical reactions and biological processes, can also lead to the formation of byproducts. However, it is possible that some micro-contaminants may persist in surface water and gradually build up over time. While restrictions exist for certain substances, such as pesticides and synthetic hormones, regarding their presence in water, there are currently no standards governing the removal of OMPs in wastewater treatment plants [Ratchnashree et al., 2023].

Various chemical, physical, and biological techniques are used to eliminate organic micro-pollutants and synthetic dyes from wastewater. These techniques include advanced oxidation process (AOP), adsorption, ultrafiltration, reverse osmosis, ion exchange, chlorination, O_3, aerobic, electro-Fenton, direct photolysis, plasma treatment, and anaerobic [Allabakshi et al., 2022; Kooshki et al., 2023; Lafi et al., 2018; Lee et al., 2020; Lim et al., 2022; Wang et al., 2013]. Among them, AOPs such as ultraviolet light (UV) with H_2O_2/O_3 and photo-catalysis are gaining popularity in removing complex organic pollutants from water and wastewater [Pandis et al., 2022; Pignatello et al., 2006; Shekhawat et al., 2021]. A detailed explanation of various practical methods for OMP treatment used in this thesis is provided in the next section.

1.3.2.1 Direct Photolysis of Pollutant under 254 nm and 222 nm Excilamps UV Radiation

UV radiation is widely recognized as an effective method for disinfection, capable of efficiently eliminating bacteria, viruses, and protozoa [Raeiszadeh et al., 2020] [Masjoudi et al., 2021]. The primary process by which UV irradiation kills germs is through direct damage to their DNA [Tatsuno et al., 2021]. Additionally, organic contaminants are eliminated by directly breaking down when they absorb UV-C protons at a wavelength of 254 nm [Imamović et al., 2022a]. The efficacy of UV irradiation in eliminating pathogens and organic micro-pollutants relies heavily on the UV dose delivered, measured in mJ/cm^2 or mWs/cm^2. Kim et al. [Kim et al., 2009] found that only a small number demonstrated significant removal from the 42 pharmaceuticals examined in actual wastewater conditions. Examples of pharmaceuticals that showed high removal include ketoprofen, diclofenac, and antipyrine. On the other hand, several other pharmaceuticals, especially antibiotics like clarithromycin, erythromycin, and azithromycin, exhibited very low degradation when exposed to UV irradiation (254 nm), even at doses exceeding 2700 mJ/cm^2. Therefore, Noutsopoulos et al. [Noutsopoulos et al., 2013] determined that with the low-pressure UV dosage commonly used to eliminate pathogens (10-80 mJ/cm^2), there will not be a significant clearance of many emerging pollutants. According to this study, the endocrine disruptors' bisphenol A and nonylphenol, as well as the non-steroidal anti-inflammatory drugs ibuprofen and naproxen, have a low degradability even at doses as high as 1000 mJ/cm^2 [Chen et al., 2006; Pablos et al., 2013; Rosenfeldt et al., 2004; Yuan et al., 2009].

In the last decade, there has been a growing interest in using KrCl* excilamps generating far UV-C (222 nm) as a potential alternative to conventional UV radiation under direct photolysis for breaking down OMPs in water treatment procedures [Xu et al., 2023a] [Li et al., 2023a]. KrCl* excilamps have the ability to cause significant photolysis of OMPs at a wavelength of 222 nm due to two specific factors. Photons with a wavelength of 222 nm possess 14% greater energy compared to those with a wavelength of 254 nm. This increased energy enables more efficient excitation of molecules. Furthermore, aromatic chemicals such as atenolol, bisphenol A, resorcinol, and naproxen, as well as other heteroaromatic OMPs like triazines, exhibit a higher absorption of light at 222 nm compared to the wavelengths of LPUV and MPUV at the same intensity [Xu et al., 2023a]. Liu et al. [Liu et al., 2023a] conducted experiments to degrade CBZ and NDMA in DI water and secondary effluents using 222 nm and 254 nm light. They found that NDMA degrades more quickly under 254 nm light compared to 222 nm light in DI water. However, CBZ exhibits the opposite trend and degrades more under 222 nm light in secondary effluents. The variation in degradation can be attributed to the disparity in molar absorption coefficients at 254 nm and 222 nm and the presence of NO_3^- in the secondary effluents. When exposed to 222 nm, the nitrates present in SE lead to the generation of hydroxyl radicals (•OH). According to several researchers [Xu et al., 2023a] [Kim et al., 2009], a chemical's structure and physical properties, such as its decadal molar absorption coefficient at 254 nm and 222 nm and the type of water matrix, greatly influence its susceptibility to degradation. There is a lack of research on the effects of UV radiation on emerging contaminants of concern. Furthermore, it has not been thoroughly proven that the intermediate products formed during photo-degradation are more resistant to degradation or harmful than the original chemicals. Various enhancements have been proposed to enhance the effectiveness of UV irradiation, such as utilizing UV-based AOPs like UV/H_2O_2 and UV/TiO_2 [Poulopoulos et al., 2019] [Li et al., 2001].

1.3.2.2 Advanced Oxidation Process

AOPs are chemical treatment procedures designed to remove organic and inorganic materials in water and wastewater. In real-world applications, AOPs usually refer to a subset of chemical processes that employ O_3, hydrogen peroxide (H_2O_2), and UV light. These processes rely on in-situ production of highly reactive •OH or sulfate radicals (SO_4) to oxidize contaminants in water and wastewater [Deng et al., 2015; Imamović et al., 2022b; Pavel et al., 2023]. The different AOP processes and their mechanism of oxidation are shown in Figure 1.9. Out of the different

AOPs, the most effective methods for pollutants degradation are photocatalysis (UV/TiO_2) and UV/H_2O_2 and these processes are discussed in detail in the further sub-sections.

AOP accelerates the elimination of hazardous contaminants by creating highly reactive •OH [Ahlawat et al., 2023]. The •OH is an extremely powerful, non-selective oxidant that causes partial or total mineralization of organic dye substances [Tijani et al., 2014]. TiO_2 is considered a more attractive choice for photocatalysts in environmental clean-up operations because of its low cost, high reactivity, high chemical stability, and non-toxic and insoluble nature [Bianco Prevot et al., 2001] [Vinodgopal et al., 1996a]. The most challenging problem in AOPs is that, after the degradation process, the extraction and reuse of the catalysts from the treated matrix is quite challenging [Joseph et al., 2023a]. Recently, many research groups reported immobilizing photocatalysts directly onto the reactor walls to remove the organic dyes from the wastewater [Teixeira et al., 2016] [Chang et al., 2010]. Still, the problem associated with this process is the decrease in photo activity after certain cycles and the removal and replacement of photocatalysts from the treated solution [133]. So, there is a need for process optimization, which eliminates the recovery and reuse of photocatalysts and simultaneously enhances the mineralization rate. According to Sun and Bolton [Sun et al., 1996], H_2O_2 suspension shows a higher •OH radical generation rate and quantum yield than TiO_2 suspension; therefore, H_2O_2 can be considered as a radical promoter in photocatalytic applications.

UV/H_2O_2 AOPs are being extensively researched as new methods for effectively removing micro-pollutants from industrial or municipal wastewater [Sturm et al., 2022] [Leong et al., 2023]. Most of the AOPs used in wastewater treatment plants, especially for municipal or industrial purposes, consist of mixtures of O_3, H_2O_2, and/or ultraviolet irradiation (UV) [Ghatak, 2014]. Nevertheless, the impact of O_3 and H_2O_2 concentrations on the removal efficiency is very complicated. Notably, the slowest rates of elimination were observed while using high dosage of H_2O_2 (i.e., H_2O_2 concentration of more than 16.6 mM or H_2O_2 ratios exceeding 0.8). Furthermore, the higher concentrations of H_2O_2 might lead to the suppression of •OH, thereby decreasing the effectiveness of micro-pollutant elimination in the UV/ H_2O_2 and UV/ H_2O_2/O_3 processes, as evidenced by Espuglas et al. [Esplugas et al., 2002] and Luo et al. [Luo et al., 2014].

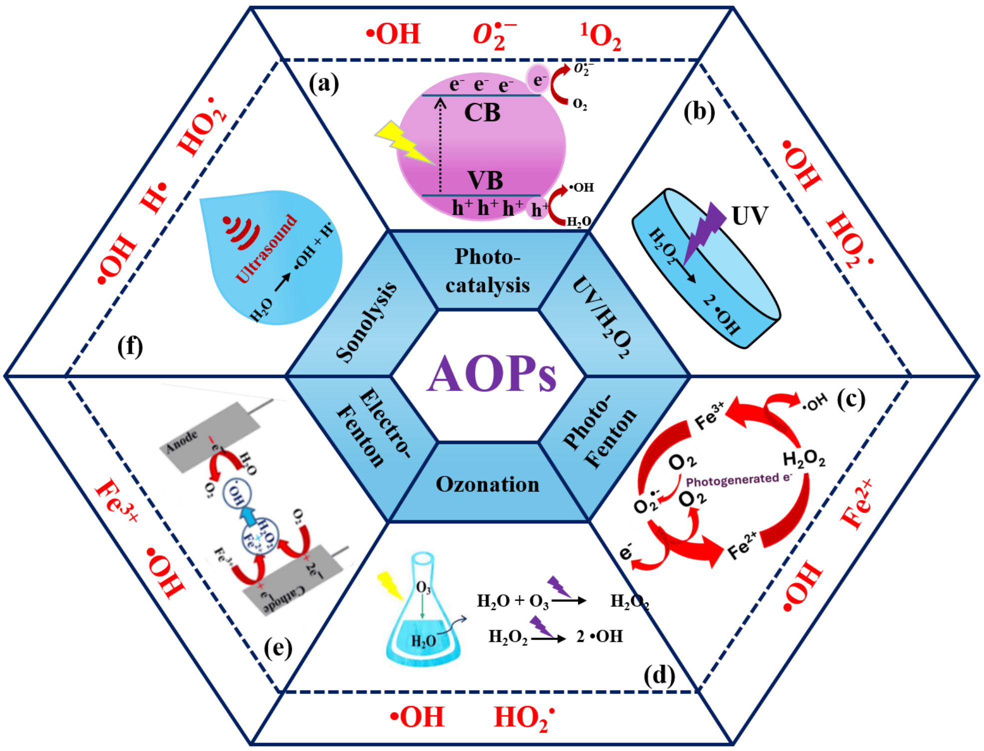


Figure 1.9. Different types of AOPs processes. (a) photocatalysis; (b) UV-H2O2 processes; (c) photo-Fenton; (d) ozonation; (e) electro-Fenton; (f) sonolysis.

During the UV/ H_2O_2 process, UV exposure to H_2O_2 with wavelengths below 300 nm results in the generation of •OH. While the UV/ H_2O_2 process is more efficient than UV photolysis, it still suffers an energy cost of 4 – 5 times greater than the results observed for ozonation [Wardenier et al., 2019]. Despite its attractive characteristics, the UV/H_2O_2 mechanism has significant drawbacks. Initially, given the relatively low molar absorption coefficient of H_2O_2 at 254 nm, large amounts of H_2O_2 are necessary to produce •OH effectively [Zhao et al., 2024]. In addition, while operating in actual water samples, the generation of •OH is even more restricted due to the presence of matrix components. These components reduce the ability of UV light to penetrate the solution, hence decreasing the effectiveness of •OH formation [Fennell et al., 2021]. Therefore, to achieve an adequate level of •OH for the breakdown of micro-pollutants, it is necessary to have a substantial amount of H_2O_2 present. Nevertheless, it is generally recommended against using high concentrations of H_2O_2 (over 10 ppm) in most commercial applications because only a small fraction (5 – 10 %) of H_2O_2 is consumed in the process. Additionally, a non-trivial H_2O_2 residual remains after treatment, which requires high chlorine demand after AOP, and its toxicity towards different aquatic organisms is very high. Therefore, it is necessary to eliminate the remaining H_2O_2 after wastewater treatment. This can be achieved by combining it with biological activated carbon treatment, raising the treatment cost [Miklos et al., 2018].

DBD is a type of NTP that can produce reactive oxygen and nitrogen species (RONS) such as O_3, H_2O_2, •OH, HO_2•, O_2•, $^1O_2$, NO_2, and NO_3 directly during electrical discharges [Jangra et al., 2023b]. DBD has emerged as a promising method for breaking down stubborn organic substances, including antibiotics, pesticides, pharmaceuticals, and phenolic compounds [Sima et al., 2023]. Nevertheless, the principal technical constraints of DBD applications arise from the low oxidation potential of certain RONS. The energy costs associated with NTP technologies are relatively high due to the limited transfer of plasma-generated species into the liquid phase, resulting in low efficiency [Sima et al., 2023]. Also, the leftover concentration of NO_3 after the degradation process, if it exceeds 50 ppm, is classified as a pollutant.

Numerous researchers have developed a hybrid system that integrates plasma with various catalysts, oxidants, and photons to overcome these limitations of NTP, reduce energy usage, and enhance the decomposition of organic wastewater. This has resulted in enhanced degradation of persistent organic compounds and improved efficiency in removing carbonaceous substances [Guo et al., 2022]. However, this approach has restrictions and has not been commercially exploited due to the difficulty in extracting the catalysts or removing residual oxidants after the degradation process. Several research studies have shown the combined effectiveness of UV-C (254 nm) and NTP in treating wastewater [Liu et al., 2023a] [Lou et al., 2023]. Moreover, little research has been conducted on using KrCl* excimer lamps (far UV-C at 222 nm) for UV/AOPs [Yin et al., 2023]. Still, no study has investigated the integration of far UV-C (222 nm) with NTP. Far UV-C can produce an abundance of •OH when reacting with NO_3^- and H_2O_2 due to higher molar absorption coefficients of NO_3 and H_2O_2 at 222 nm. So, the integration of plasma and far UV-C has the potential to enhance the production of reactive species, specifically •OH, expand the reaction surface area, improve the specificity of the degradation process, and eliminate the need for external addition of oxidants. To the best of our knowledge, there is no literature available on the effectiveness of NTP combined with far UV-C in degrading micro-pollutants compared to standard AOPs.

As stated earlier this thesis is centered on the design and development of different excilamps to enhance the efficient production of UV radiation. Additionally, in environmental applications, to utilize these sources in the treatment of industrial wastewater. The study is focused on investigating the fundamental mechanisms involved in the removal of OMPs and also to assess their potential environmental impacts through detailed analysis of these elements.

1.4 Research Plan

1.4.1 Research Gap in Literature

The above comprehensive literature review has illuminated the following several critical research gaps that merit attention and further investigation.

1. The maximum efficiency of KrCl* and XeI* excilamps has been computed theoretically as 31% and 37%, respectively. However, the experimentally achieved efficiencies have been limited to 4% to 12%. This discrepancy between theoretical and experimental efficiency can be attributed to the fact that a significant portion of the electrical energy is lost as heat rather than contributing to the radiation process. Therefore, there is a need for experimental efforts to improve the electrical input to optical output conversion efficiency of excilamps with minimal lamp heating. Also, designing, developing, and optimizing a 222 nm Far UV-C light source with high efficiency along with a diffuse discharge and a narrow band emission at low pressures with minimal heating is critical for advancing this technology.

2. Although cylindrical-shaped excilamps have been extensively studied, there remains a significant opportunity to explore planar-type excilamps for achieving higher efficiency in UV radiation generation. Another crucial challenge is the development of new generations of narrow-band UV radiation sources with enhanced efficiency. Currently, there is a notable gap in studies evaluating the bacterial inactivation efficiency of KrCl* excilamps on various surfaces, which is essential for understanding their suitability in occupied spaces and enclosed environments. Additionally, there is a need to address the impact of repetitive exposure to far UV-C radiation on the surface characteristics of test materials.

3. UV/photocatalytic processes offer significant effectiveness in industrial wastewater treatment. However, challenges emerge in the extraction of catalysts from the treated wastewater. Research into methods eliminating the need for catalyst recovery while maintaining process effectiveness is imperative. Furthermore, the mineralization time associated with various catalytic processes is prolonged and necessitates reduction through integration of different methods. Additionally, assessing the toxicity of post-treated water for its potential reuse in agricultural applications remains an unexplored area that demands attention.

4. The molar absorption coefficient and quantum yield of various organic pollutants are notably higher at 222 nm compared to 254 nm. However, existing research primarily concentrates on degrading OMPs from artificial wastewater, lacking sufficient explanation of the degradation mechanism. Hence, there is a need for a rigorous study to elucidate the mechanisms of 222 nm UV radiation in degrading organic pollutants within real water matrices. Additionally, optimizing the process to achieve minimal electrical energy per order (E_{EO}) requirement is essential for practical application.

5. The treatment of emerging organic micro-pollutants (OMPs) through direct photolysis and AOPs has been largely studied. However, AOPs typically require additional chemicals beyond those naturally present in the wastewater matrix, which can complicate the process. A research area that remains largely unexplored is the integration of non-thermal plasma with excimer UV light sources, which has the potential to eliminate the need for adding external chemicals. Specifically, the potential of combining plasma with far UV-C (222 nm) in direct photolysis for the degradation of OMPs remains unexplored and requires deeper research efforts.

1.4.2 Formulation of Research Objectives

1. To study and develop DBD-based planar and cylindrical excimer/exciplex plasma systems which will be able to produce ultraviolet (UV) radiations in the germicidal wavelength range UV-C (200-280 nm), particularly 222 nm (KrCl*) and 253 nm (XeI*) and hence to treat the different microorganisms, i.e., gram-positive and gram-negative bacteria.

2. To characterize these sources for electrical power consumption, UV radiation intensity, and electrical input to optical output conversion efficiency by optimizing the high voltage electrode geometry, gas pressure, applied voltage and supplied frequency. Also, to check their bactericidal efficiency on different materials surfaces, i.e., stainless steel, aluminium, glass, and high-density polyethene.

3. To study and develop modified-XeI* excilamps by coating its outer electrode with titanium dioxide (TiO_2) nanoparticles that can generate reactive species and active ions along with 253 nm UV radiation to enhance the dye degradation and mineralization efficiency. Also, to understand the mechanism of the dye degradation under the hybrid XeI* excilamp along with the toxicity analysis of treated wastewater on seed germination in soil.

4. To utilize the developed KrCl* excilamp emitting 222 nm far UV-C radiation for the direct photolysis and under AOP treatment of azo dye in real wastewater and to understand the degradation mechanism under far UV-C radiation with H_2O_2 as a radical's promotor and optimize the process for minimum E_{EO} requirement.

5. To develop and characterize a double dielectric barrier discharge (DDBD) plasma reactor for the production of reactive oxygen and nitrogen species (RONS) and to investigate the role of DDBD plasma produced NO_3^-, nitrites (NO_2^-), and H_2O_2 under planar KrCl* excilamps irradiation (222 nm) in the mineralization and degradation of different organic micro-pollutants (OMPs).

1.4.3 Thesis Outlines

This research was carried out through standardized experimental techniques in order to accomplish the objectives of this thesis. This thesis includes a comprehensive account of the methodology and experiments employed, as well as the analysis and discussion of the resulting data. Additionally, it concludes with a summary of the thesis content and provides recommendations for future investigations on Far UV-C Excimer sources.

The thesis is majorly divided into two parts: First parts explain the development and characterization of the excilamps for their electrical to optical conversion efficiency and their absolute intensity of irradiation. The second part is based on the uses of the developed excilamps for the surface's sterilization, wastewater treatment and the bacterial inactivation efficiency of these sources. The content is divided into 7 chapters, including the first chapter which provides an introduction to UV disinfection and the newly developed far UV-C excilamp technology for health and environmental applications.

Chapter 1 also presents a comprehensive examination of the principles, applications, and difficulties associated with the inactivation of microorganisms using excimer UV light sources. The importance of utilizing excimer UV-C and Far UV-C in the environment and health sectors is discussed in detail in this chapter. In addition, the existence of a knowledge gap is emphasized, and research objectives are formulated accordingly to address the knowledge gap. The remaining chapters in this thesis are structured as follows:

Chapter 2: This chapter describes the different experimental and diagnostic techniques used for material synthesis, excilamps fabrication and characterization. A brief introduction of the irradiation technique is also described. The details of measurements by the used diagnostic techniques are presented at appropriate places in subsequent chapters.

Chapter 3: In this chapter, detailed studies on the development of the KrCl* excilamp is provided. Optimization of high voltage electrodes has been carried out to minimize the lamp heating without using any external cooling. Applied voltage, frequency and gas pressure are optimized to get high electrical-to-optical conversion efficiency of the lamp. The radiant output power of the excilamp has been calculated and the overall electrical input to optical output has been reported. The bacterial inactivation efficiency of the low-pressure narrow band KrCl* excilamp on gram negative and gram-positive bacteria is also discussed. Morphological studies of treated bacteria have been included to correlate the results.

Chapter 4: In this chapter, the design and development of a mercury-free DBD-based modified XeI* excilamp is presented in which one of the electrodes is coated with TiO_2 nanoparticles to enhance the mineralization efficiency of the treated dye. This modified XeI*-excilamp generates 253 nm UV-C light and reactive oxygen species from TiO_2 coated electrode simultaneously. The transportation mechanism of different active ions and reactive species from the gas phase to the aqueous phase has been discussed. The developed modified excilamp is the first of its kind and has been utilized to degrade RB5 azo dye effectively. The effects of different concentrations of catalysts loading, initial concentrations of dye, solution pH, and different concentrations of H_2O_2 are examined at different treatment times for the degradation of RB5 dye. Instead of loading photocatalysts in the wastewater suspension, we coated the TiO_2 on the electrode of the excilamp and utilized H_2O_2 as a radical promoter with varying concentrations of 0.013% to 0.039% v/v (100 ppm). In order to determine the toxicity of dye wastewater treated using various processes, radish seeds were germinated in soil using the treated dye wastewater and deionized water (DIW), and the results were analyzed. An understanding of how reactive species in the gas and aqueous phases interact with wastewater constituents and an effective strategy to valorize treated effluent is discussed.

Chapter 5: This chapter describes the degradation of reactive black 5 (RB5) in artificial wastewater using a 222 nm Kr/Cl_2 excimer source under direct photolysis and an AOP using TiO_2/H_2O_2. The effect of solution pH, catalyst concentration, 222 nm intensity, initial concentration of dye, and addition of H_2O_2 (maximum 10 ppm) is discussed and the degradation rate constant is reported for each method. The molar absorption coefficient, quantum yield of RB5 at 222 nm and the electrical energy per order (E_{EO}) from different treatment methods have been presented in this chapter. A possible degradation pathway has been established based on Fourier transform infrared spectroscopy (FTIR) and high-resolution mass spectrometry (HRMS) analysis. The phytotoxicity of the treated wastewater was checked for its reusability in agriculture purposes by analysing the impact of treated wastewater from different processes on the germination percentage, root and shoot length of Raphanus sativus seeds.

Chapter 6: In this chapter, a new approach for the degradation of the two key OMPs, namely Carbamazepine (CBZ) and Sulfamethoxazole (SMX), in deionized water (DIW) and tap water (TW) has been discussed. The study presents the utilization of cold plasma and KrCl* excilamp (far UV-C at 222 nm), both based on DBD plasma along with a conventional UV (LPUV at 254 nm) lamp. The combinations are created like plasma + LPUV, and plasma + KrCl* excilamp for the degradation of SMX and CBZ. Two plasma devices are firstly developed for this purpose: a 222 nm planar KrCl* excilamp and a DDBD-based device. The concentration of long-lived (H_2O_2, NO_2 and NO_3) and short-lived species (OH radical) in the different water matrices have been quantified. Accordingly, the role of plasma-produced reactive species in the degradation of CBZ and SMX under KrCl* excilamp has been reported in this chapter. For both methods, the degradation rate, pseudo-first-order rate constant, and E_{EO} are described. The possible degradation pathways have also been suggested using high-resolution mass spectrometry (HRMS).

Chapter 7: In this chapter, we have concluded the findings of entire research work and described the future scope of the thesis