1
Introduction

1.1 Background

Food safety is a critical issue for both the food industry and food services, as the consumption of contaminated food can lead to foodborne illnesses. The World Health Organization reports that approximately 600 million people, nearly 1 in 10 individuals worldwide, suffer from foodborne diseases each year. Tragically, these illnesses contribute to an estimated 4,20,000 deaths annually, highlighting the importance of ensuring food safety at every stage of production and distribution. Dairy products can serve as significant reservoirs of foodborne pathogens, as they offer favorable environments for the growth of various microorganisms. This is due to their high nutrient content, which includes carbohydrates, lipids, proteins, essential amino acids, enzymes, vitamins, and minerals. Therefore, ensuring the production of high-quality goods that do not present any hazards to customer well-being is a major challenge in the food industry. The dairy business faces significant difficulty due to the potential contamination of dairy products, which can originate from diverse sources at different stages of manufacturing. Hence, the production of diaries necessitates stringent quality control measures to mitigate the potential hazards of foodborne illnesses.

Thermal processing is a conventional method employed in the dairy industry to guarantee food safety and prolong the shelf life of products by eradicating harmful microbes and preventing rotting, as well as deactivating enzymes. Heat treatments, while effective, can have adverse effects on food by altering sensory attributes like color, texture, and flavor. Furthermore, it can lead to a decrease in the nutritional content, including the reduction of some bioactive compounds, the deactivation of enzymes, the loss of vitamins, the oxidation of lipids, and the denaturation of proteins, ultimately culminating in the production of low-quality food. Another drawback is that thermal processing necessitates significant energy consumption, which may compromise the ultimate value of the product to assure profitability in the sector.

This problem is further exacerbated in context to the Indian milk chain because the milk value chain in India is complex and involves multiple stages, from production to consumption, as shown in Figure 1.1. Smallholder dairy farms dominate milk production in India. The herd number is limited, and it is raised in a manner that is closely interconnected with crop production. According to a study by Kumar et al. [Kumar et al., 2018], almost 75% of milk production in India came from farms with less than 1 hectare of land (marginal farms) and farms with 1-2 hectares of land (small farms). India possesses over three times the number of 'dairy' animals compared to the USA, with the bulk (nearly 80 percent) being maintained in herds consisting of 2 to 8 animals [Garcia et al., 2003] and hand milking remains a viable option for small-scale dairy farmers or in areas with limited access to technology. The whole milk from the udder of the cow has a Methylene Blue Reagent Test (MBRT) value of greater than 5.5 hours but these small-scale dairy farmers have limited power to chill the milk and due to unavailability of the preservation techniques it suffers spoilage. The milk is collected by village collection centers (VCC) from all the small-scale dairy farms and by this time, the MBRT of the milk comes down to 3-4 hours. Different VCC's then supply the milk to the Bulk Milk Chiller (BMC), generally placed in cities, and BMC take 2-3 h to chill milk to 4 ˚C. By the time milk reaches BMCs and all milk reaches a temperature of 4°C, MBRT comes down to 1 h.

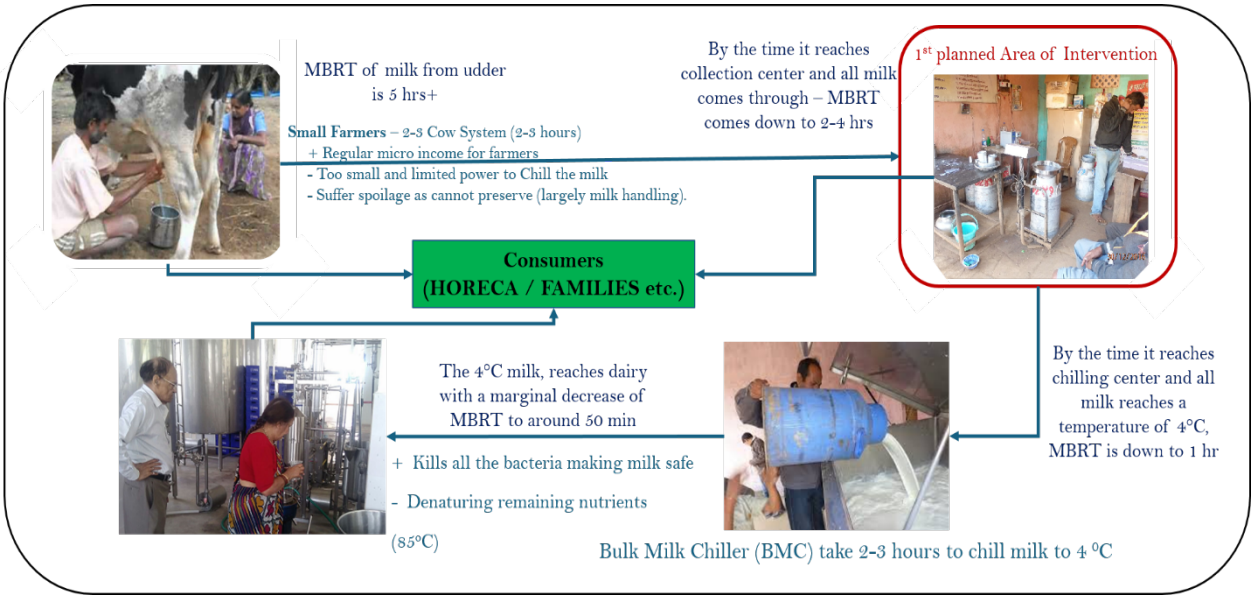


Figure 1.1: Schematic of the milk chain in India.

The industrial acceptable limit for MBRT is more than 4 h and for these purposes, the milk is processed by the pasteurization process and heated up to 85 ˚C. By this process, the MBRT increases up to 5.5 hours because it kills all the bacteria in the milk, but it denatures remaining nutrients from the milk. Then the pasteurized milk is supplied to the consumers. Throughout this chain, several issues like poor hygiene practices at the production level, inadequate cooling and storage facilities, transportation challenges, contamination during processing, adulteration Issues, can lead to bacterial contamination, affecting the quality and safety of milk. The Milk chain in India is quite complex and needs the interventions at farmers level and VCCs to improve the nutritional value of the milk.

Various advanced techniques in food processing are being developed to ensure the safety, quality, and acceptability of food, providing effective alternatives to traditional heat treatments. These methods help prevent contamination, minimize damage to food structure, and preserve its physicochemical, nutritional, and sensory properties. Among the advanced techniques are cold plasma, Ultraviolet (UV) radiation, ohmic heating, high hydrostatic pressure, pulsed electric fields, and ultrasound [Mukhtar et al., 2022] [Harikrishna et al., 2023]. UV radiation, in particular, has emerged as a highly promising and commercially viable technology. A survey of industry professionals, government officials, and academics in North America and Europe revealed that UV radiation ranks among the top technologies with significant commercial potential in food production [Maherani et al., 2016]. Additionally, products treated with UV technology were found to exhibit higher quality, improved safety, and extended shelf life. However, there is limited research on the impact of UV radiation on the microbiological safety and quality of dairy products. Therefore, the aim of this thesis is to explore various UV wavelengths and cold plasma technologies for their potential application in milk processing.

1.2 About Ultraviolet (UV) Radiation

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 1.2. The subset of UV-C radiation with wavelengths in the 200-230 nm range is known as Far UV-C [Diffey, 2002]. These spectral areas are very specific and have various potential applications, as shown in Figure 1.2. Exposure to vacuum ultraviolet (VUV) radiation has been shown to smooth polymer surfaces, as demonstrated by previous studies [Fozza et al., 1999].

Additionally, VUV light has been effective in inactivating RNA viruses [Jalali Milani et al., 2022]. UV-B radiation, particularly within the 310 nm narrow band range, has proven to be a beneficial long-term therapy for various skin disorders such as psoriasis, vitiligo, and eczema [Gambichler et al., 2005]. In the case of toenail fungal infections, certain wavelengths of UV light offer a safer alternative to conventional systemic medications. Moreover, UV-A radiation is extensively utilized in printing industries, including applications like UV inkjet printing and automated UV printing [Scotton et al., 2021]. The UV-C range (200-280 nm), which has long been recognized for its potency in disinfection and sterilization, remains one of the most effective methods for microbial control [Keklik et al., 2012] [Trivellin et al., 2021].

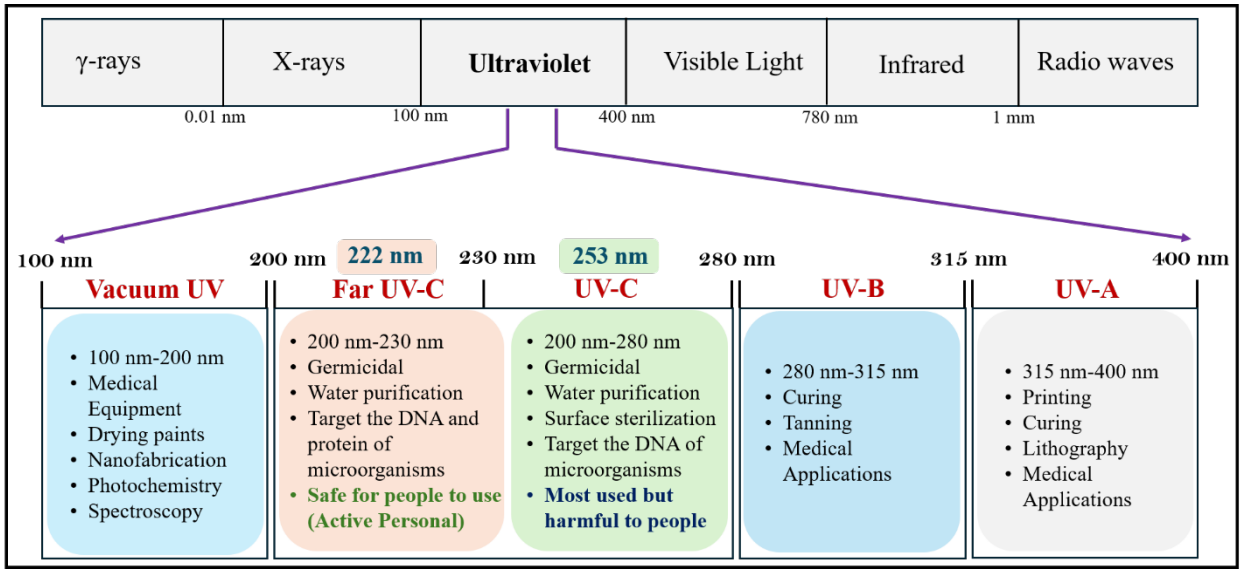


Figure 1.2: UV radiation and wavelengths, and applications of UV radiation in different sectors.

1.2.1 Potential Applications of the Ultraviolet radiations in Food Sterilization

Utilizing ultraviolet (UV) light to render microorganisms is a compelling alternative, as it is a commercially accessible technology that does not require the employment of chemicals. Certain applications, like water treatment, have been extensively developed, whilst others, such as food processing applications, still hold promises. There is some research available with conventional UV for the food processing [Wu et al., 2025] [Lisboa et al., 2024].

Recently, the use of UV radiation has garnered growing attention in the food industry for its ability to decontaminate both liquid and solid surfaces [Chawla et al., 2021b] [Bintsis et al., 2000]. As a non-thermal method, it effectively inactivates microorganisms, including pathogens and spoilage organisms [Lu et al., 2021]. UV radiation stands out as a physical intervention that doesn't induce radioactivity in treated products, unlike ionizing methods such as gamma radiation, which can leave residual reactivity [Jo et al., 2012].

UV light inactivates microorganisms through multiple mechanisms, depending on the wavelength used during treatment [Dai et al., 2012]. Microbial inactivation can occur either directly, when the DNA absorbs UV light, or indirectly through other cellular processes [Rastogi et al., 2010]. The primary mode of action involves disrupting DNA replication by causing lesions. UV-C radiation, particularly within the short wavelength range of 200-280 nm, is most effective at damaging DNA, making it the most lethal and germicidal part of the UV spectrum for a wide range of microorganisms, including harmful bacteria and viruses [Kciuk et al., 2020].

Conventional UV light has been extensively researched for the disinfection of milk and dairy products (Table 1.1). Various types of milk, kashar cheese, fresh cheese, and white American cheese have been tested in these studies. Results showed a significant decrease in microbial counts

across different dairy products. The efficiency of UV treatment depends largely on factors such as UV dose and the distance from the light source, which greatly influence bacterial reduction. However, a key limitation of UV radiation is its shallow penetration depth, making it primarily non-suitable for surface decontamination of solid foods like cheese.

Table 1.1: Effects of ultraviolet radiation technology on the microbial inactivation of dairy products.

Sr. No.	Dairy Products	Micro-organisms	UV Processing Parameters	Results	Ref.
1.	Cottage Cheese	*Pseudomonas spp*	Pulsed UV Light 16 J/cm^2 0.5 ms pulse duration	Reduction about 1.5 log were obtained; No effect on the sensory attribute (taste)	[SMITH, 1963]
2.	Goat's Milk	*Listeria monocytogenes*	UV apparatus designed to increase UV penetration 15.8 ± 1.6 mJ/cm^2	Reductions above 5 log of *L. monocytogenes* were obtained	[Matak et al., 2005]
3.	Raw Milk	*Staphylococcus aureus*	Pulsed ultraviolet light 3 pulses/s 8 cm lamp-product distance 1 to 3 passes through the system 20-40 ml/min 1, 2, 3, 4, 5, 10, 15, or 30	*S. aureus* count decreased 0.55 to 7.26 log CFU/ml Total inactivation was obtained as multifunctional, depending on the sample distance, number of pass and flow rate combinations.	[Krishnamurthy et al., 2007b]
4.	Raw Milk	*Listeria monocytogenes*	Dose 21.3 mJ/cm^2 Time 60 min at 25 °C	1-6 log10 reduction (in 60 min)	[Lu et al., 2011]
5.	White American Cheeses	*Penicillium roqueforti, Listeria monocytogenes*	Pulsed UV Light 3 pulses/s 5.8 and 13 cm lamp product distances 5, 30, and 60 s	Maximum reduction was obtained 40 s at 5 cm Decrease ranged from 1.32 to 1.24 log CFU/cm^2	[Can et al., 2014]
6.	White Cheddar and Process Cheeses	*Pseudomonas fluorescens, Escherichia coli ATCC 25922, Listeria innocua*	Xenon flash lamp, 3 pulses/s 5.8 cm lamp-product distances 1.02, 3.07, 6.14, 9.22 and 12.29 J/cm^2 fluence levels	Reduction about 3.37, 3.74, and 5.41 log UFC/g for *Listeria innocua, P. Fluorescence*, and *E. coli*	[Proulx et al., 2015]

7.	Skim Cow Milk, Whole Cow Milk, and Whole Sheep Milk	*Bacillus subtilis spores*	UV-C pre-treatment 254 nm 2.37 ± 0.126 J/ml Combined with thermal treatment at 110 degree C for 30 s	Reduction about 6, 2.90, and 1.1 log CFU/ml in bovine skim milk, bovine whole milk and ovine milk	[Ansari et al., 2019]
8.	UHT Whole and Skim Milk	*Bacillus subtilis spores*	LPM UV-C Lamps (254 nm) Dose ranging from 10 to 160 J/ml	Initial concentration about 6 log CFU/mL Doses from 100 J/ml with several passes produced the best lethality results (above 4 Log CFU/ml) Effective distance from the UV-C source: 0.02 mm for whole milk and 0.06 mm for skim milk.	[Martinez-Garcia et al., 2019]
9.	Raw Soya Milk	*E. coli W1485 and Bacillus cereus spores*	Coiled tube with UV reactors at a constant residence time of 11.3 s with UV-C dose of 11.187 mJ/cm^2	Maximum reductions of 5.6 log10 CFU/ml of E.coli and 3.29 log 10 CFU/ml of *B. cereus spores*.	[Bandla et al., 2012]
10.	Goat Milk	E. coli	Pulsed UV Light Generated using an exciplex laser unit Doses of 5000 and 10,000 mJ/cm^2	6 log reduction achieved using 10,000 mJ/cm^2 of pulsed UV.	[Kasahara et al., 2015]
11.	*Donkey Milk*	*L. inoccua, S. aureus, B. cereus, Cronobacter sakazakii, E. coli, and salmonella enteritidis*	Low power UV unit UV Dose: 0, 91.8, 275.4, 459, 642.6, 826.2, 1000.8, 1100, 1200, and 1300 J/L Intensity 17.7 mW/cm^2 Flow rate 4000 L/h	*L. innocua* was the most UV-C resistant, complete inactivation at 1100 J/L, while the rest of the bacteria tested was destroyed by the range of 200-600 J/L	[Papademas et al., 2020]

The European Food Safety Authority (EFSA) has indicated that exposing milk to UV-B radiation can boost its Vitamin D3 content by converting 7-dehydrocholesterol into Vitamin D3. Moreover, studies have shown no major alterations in the nutrient profile of UV-treated milk (EFSA, 2016) [Fiege et al., 2024]. However, variations in process parameters might lead to some changes, such as shifts in the fatty acid composition, an increase in thiobarbituric acid reactive substances, and protein precipitation [Atik et al., 2021a]. Regarding the sensory qualities of goat milk post-UV treatment, alterations in odor have been observed, likely linked to the treatment

conditions [Matak et al., 2007]. Excessive UV exposure may impact the physicochemical and sensory properties of the milk, potentially causing color alterations, protein oxidation due to UV light absorption by amino acids, and a decrease in pH levels [Schubert et al., 2024]. These findings suggest that low UV doses have minimal adverse effects on milk and dairy products, though higher doses have been associated with nutritional loss, texture degradation, and the formation of undesirable compounds. While only a few studies have explored the potential negative effects of UV treatment on the sensory and physicochemical properties of dairy products, more research is needed in this area. The convention UV sources itself have various challenges, which will be discussed in the next section, making them difficult to utilize for food sterilization purposes. So far, no research has utilized narrow band Far UV-C excilamps (222 nm) and UV-C excilamp (253 nm) for the sterilization of milk and this needs to be researched in detail.

UV light plays a role in accelerating oxidation processes and initiating free radical reactions [Wei et al., 2024]. It generates superoxide radicals (SOR), lipid radicals, and hydrogen peroxide (H_2O_2) [Tumilaar et al., 2024]. These radicals can lead to protein fragmentation, protein and carbohydrate crosslinking, unsaturated fatty acid peroxidation, and disruption of membrane permeability. UV exposure can also result in the denaturation of key components such as proteins, amino acids (particularly those with aromatic groups), and enzymes in milk, leading to texture modifications. When UV photons are absorbed by water, they produce OH- and H+ radicals, which may trigger alterations in other food components [Koutchma, 2009]. High doses of UV light can cause changes in the chemical composition of food products and lead to the degradation of their quality [Csapó et al., 2019]. Therefore, it is crucial to optimize the UV disinfection process to maintain food consistency while ensuring safety.

The germicidal effectiveness of UV-C radiation in food surface decontamination is influenced by various factors, including the process conditions, the characteristics of the food product, and the nature of the microorganisms being targeted. Key factors include the UV dose, duration of exposure, location and type of microorganisms, their ability to regenerate, and the surface properties of the food. A thorough understanding of these variables is crucial for selecting the appropriate radiation parameters to achieve effective microbial inactivation as shown in Figure 1.3.

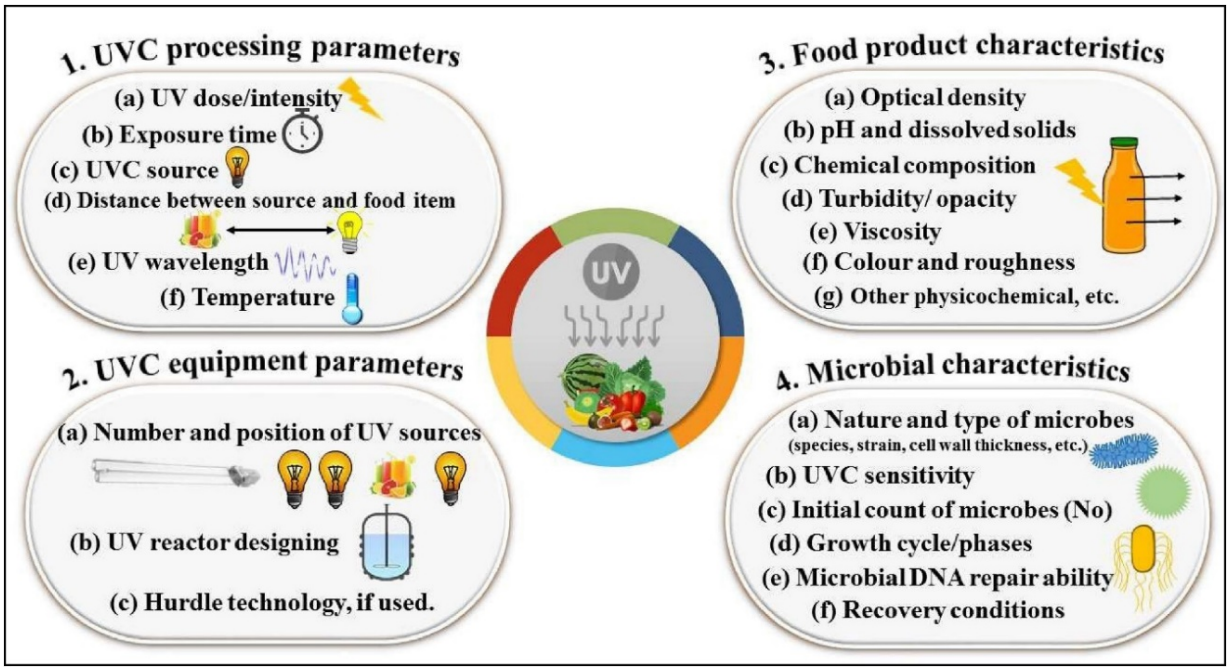


Figure 1.3: Important factors that affect the UV-light processing of food items.

The wavelength and UV dose are the primary process-related factors that impact microbial inactivation. Other physical aspects, such as the flow pattern and the design of the UV equipment, also play significant roles [González et al., 2023]. Maximum germicidal efficiency is

attained at wavelengths near the DNA absorption peak, which depends on the type of UV lamps used [Delorme et al., 2020]. In liquid food applications, the ability to inactivate microorganisms is further influenced by the absorption spectra of the food matrix across different wavelengths [Forcato et al., 2005]. For instance, as illustrated in Figure 1.4, our studies show that the milk absorbs 222 nm UV radiation more effectively than 253 nm (the typical wavelength of conventional UV lamps).

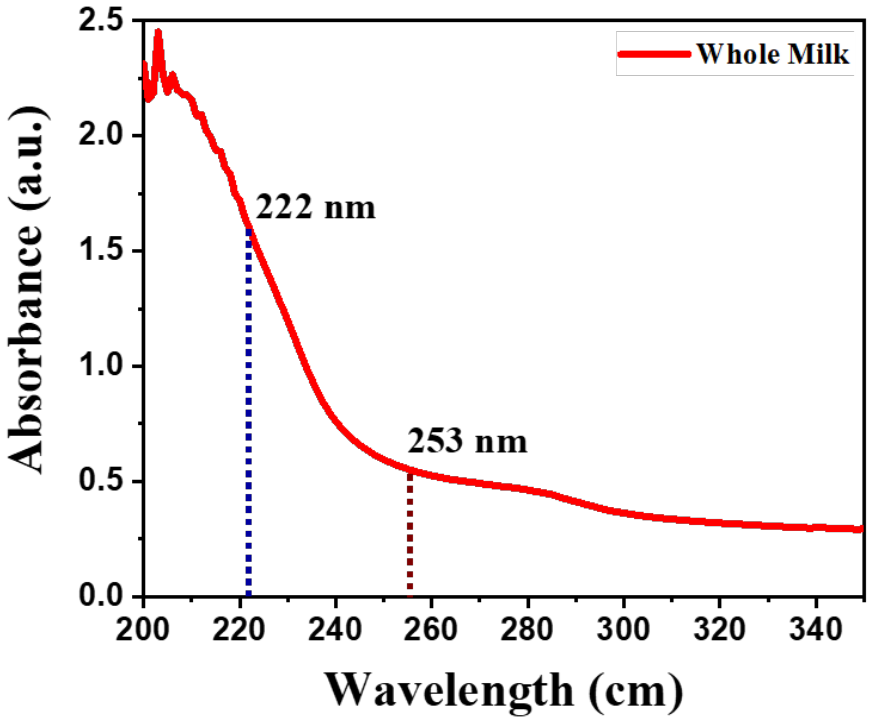


Figure 1.4: Absorption spectra of Milk at different UV wavelengths.

According to studies, far UV-C light at 222 nm from excimer lamps offers an effective method for disinfecting harmful microorganisms while providing added safety for mammalian skin and eyes, due to its limited penetration depth and higher absorption by biological tissues [Id et al., 2020]. However, the potential of 222 nm UV light for sterilizing milk remains largely unexplored. The disinfection effectiveness of a UV source is typically measured as UV fluence (mJ/cm^2), which is influenced by factors such as exposure time, intensity of irradiation, and the medium in which bacteria are inactivated [Ahlawat et al., 2023] [Ahlawat et al., 2022]. The efficiency of bacterial inactivation is influenced by the emission characteristics of the UV source, whether narrow or broad spectrum, as well as the type of discharge, such as filamentary or diffused. These factors play a critical role in determining the conversion efficiency from electrical energy to optical output. Further research is required to better understand and optimize these variables.

1.2.2 Challenges Associated with Conventional UV Sources

As discussed, UV radiation especially in the UV-C range (i.e., 200-280 nm), is highly effective at disrupting microbial replication, making it valuable for applications like water disinfection [Song et al., 2016] and air purification [Reed, 2010], surface decontamination [Elgujja et al., 2020], milk sterilization [Guamán-Lozada et al., 2023], and sanitizing agricultural [Saneya M. El Neshawy et al., 2024], poultry products [Haughton et al., 2011], etc. However, despite its promising potential, UV disinfection faces two main challenges in terms of sustainability. First, conventional UV lamps contain mercury, which raises environmental concerns. Second, the

inactivation efficiency of these sources is sometimes hindered by photo-reactivation of microorganisms and potential health impacts.

Currently, mercury-based UV lamps, particularly fluorescent types, dominate the market, with global production reaching approximately 1.2 billion units annually. These lamps contain varying levels of mercury, depending on their type [Mayor-Smith et al., 2021]. Low Pressure (LP) lamps, which emit at 254 nm, contain between 5 to 50 mg of mercury. LP high-output lamps hold around 26 to 150 mg, while medium pressure UV lamps contain significantly larger amounts, ranging from 200 to 400 mg. The widespread use of these lamps, coupled with their mercury content, raises environmental concerns, highlighting the need for more sustainable alternatives in UV disinfection technologies. The disposal of mercury-based UV lamps contributes to significant quantities of hazardous mercury-laden waste [John, 1999]., raising serious environmental concerns due to mercury's high toxicity. Furthermore, these lamps are associated with potential risks, such as explosive failures that can release toxic mercury into both water and air, posing substantial health threats. Technical limitations, including long start-up times, filament issues, sleeve breakages, size restrictions, and difficulties in repair, make these lamps less ideal for applications like food sterilization [Raposo et al., 2003]. Additionally, the 254 nm UV radiation emitted by these lamps poses health risks, as it can penetrate the skin and eyes, leading to conditions like skin cancer and cataracts [Raposo et al., 2003]. As a result, their use is restricted in environments where people are present. In response to these challenges, global research is focused on developing mercury-free alternatives. Notable advancements include the exploration of excimer radiation technology, which generates UV to deep UV light using dielectric barrier discharge (DBD) plasma. The non-thermal nature of this technology makes it particularly promising for applications such as food sterilization [Prakash et al., 2017] [Ahlawat et al., 2024b].

1.3 About Dielectric Barrier Discharge (DBD)

Dielectric Barrier Discharge (DBD) is one of the most common methods for generating plasma. In 1857, W. Siemens introduced an innovative electrical gas discharge that produced ozone (O_3) from oxygen at atmospheric pressure, and this method later became known as DBD [Tański et al., 2023]. This technology utilizes insulating dielectric barriers to prevent the discharge from transitioning into an arc, enabling stable and efficient plasma generation across a range of applications [J. J. Thompson, 1879]. According to Siemens' studies, the DBD setup consists of two concentric coaxial glass tubes separated by a small gap. Dielectric Barrier Discharges (DBDs), also known as barrier discharges, are produced in configurations where at least one dielectric layer is positioned between two electrodes [Brandenburg, 2017]. The geometry of a typical DBD is straightforward, often involving two parallel electrodes with a dielectric barrier placed between them, as depicted in Figure 1.5. When a potential difference is applied between the electrodes, a uniform electric field is generated, and the dielectric barrier helps prevent the formation of sparks and arcs by limiting current flow. The breakdown voltage depends on factors such as the electrode spacing, gas pressure, and the type of gas used. DBDs are commonly powered by Alternating Current (AC) to prevent excessive charge buildup on the dielectric barrier, which could otherwise extinguish the plasma. The AC voltage ranges from 1 to 100 kV, and the frequency can vary between 50 Hz and 500 kHz [Ollegott et al., 2020] [Brandenburg, 2018].

DBD-based plasmas are highly attractive for industrial applications, as discharges occur when the electric field outside the dielectric reaches a critical threshold [Kogelheide et al., 2020] [Pavon et al., 2007]. Under atmospheric pressure, these discharges often adopt a filamentary form due to the streamer discharge mechanism. In DBDs, the charge accumulation on the dielectric generates an opposing electric field that counters the applied AC voltage during the first half of the cycle. This prevents streamers from forming in the same location, resulting in a statistically dispersed distribution of streamers across the discharge gap [Pavon et al., 2007].

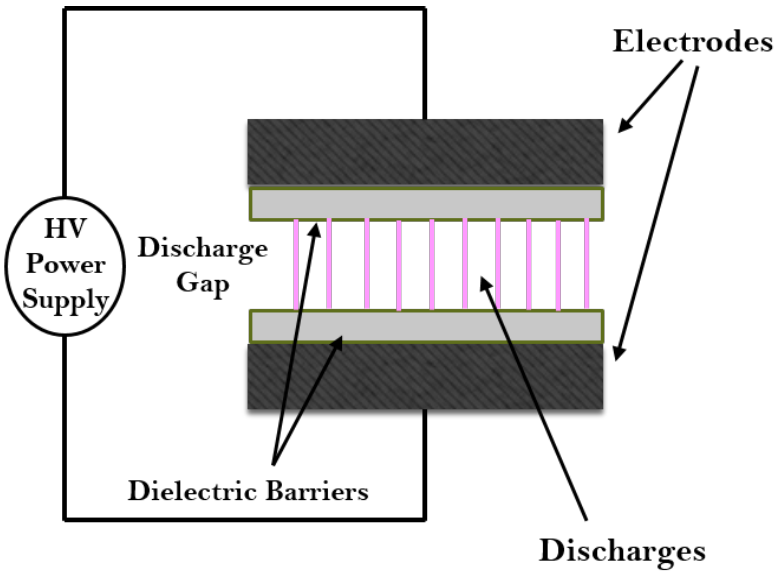


Figure 1.5. Typical dielectric barrier discharge configuration for plasma Generation.

Beyond filamentary discharges, DBDs can also operate in a homogeneous or diffuse mode. The spatial distribution of micro discharges in DBDs can vary significantly depending on the applied voltage waveform, sometimes forming distinct glow discharge regions, symmetrical patterns, or blurred cone-shaped areas [Shcherbanev et al., 2019]. As the applied power increases, the initially non-uniform and patterned discharges tend to become more homogeneous. This homogeneity is crucial for maintaining low peak current densities, which is essential for optimizing the conversion of electrical energy into radiative energy in plasma based light sources [Rajasekaran et al., 2010]. Additionally, the physical characteristics of DBDs directly influence the radiation output, meaning that optimizing light conversion efficiency or radiation intensity can be achieved through specific discharge configurations and external adjustments [Sosnin et al., 2011].

1.3.1 Light Generation through DBD Plasmas and Mechanism of Excimer Formation

Typical DBD geometries used for the cylindrical and planar excimer lamps are shown in Figure 1.6 (a), and 1.6 (b) & (c), respectively. Mostly, excimer lamps are designed with coaxial geometry because it provides higher efficiency. However, these lamps can vary in terms of size, the type of gas used, and their power sources. These variations allow for flexibility in their application, enabling excimer lamps to be tailored to specific requirements depending on the desired wavelength, power output, and operational environment [Brandenburg, 2017]. The quartz tubes also function 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. 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]. 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 Table 1.1.

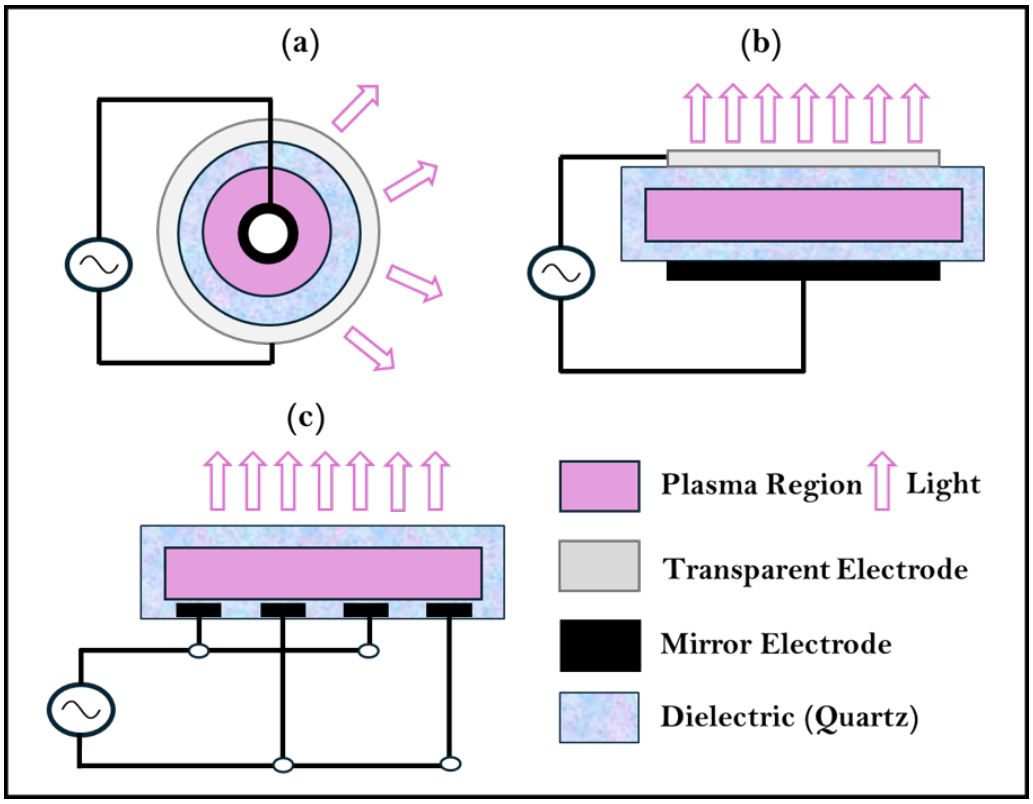


Figure 1.6. Basic configurations of DBDs used for the generation of light.

Regardless of the excitation method used, both excimer and exciplex molecules undergo a similar energy relaxation process between their electronic states within the medium [Florez et al., 2018]. The interaction between ionized and excited states, linked through various potential energy curve interactions, leads to the relaxation of the gas medium via non-radiative sequential population of these excited states [HASEGAWA et al., 2004]. The transition from the lower excited states of excimer and exciplex molecules back to their ground states is radiative, with a significant energy difference between these states. This energy difference results in the efficient conversion of energy from the gas phase into electromagnetic radiation, contributing to distinct emission transitions in the ultraviolet and vacuum ultraviolet regions of the spectrum [Sosnin et al., 2006]. Among rare gas halogen exciplex molecules, the B-X transition is the most intense, while weaker transitions such as D-X, D-A, and C-A, as well as emission bands related to halogen dimers, also occur [Zhang et al., 1998]. All transitions and their respective emissions are shown in Table 1.2 for different combinations of rare gas and halogen atoms. Choosing the right UV source is extremely important as it can increase the efficiency of microbial inactivation by increasing the penetration of UV light into food.

Exciplex formation can happen through two key reactions: a three-body ion-ion recombination or a harpoon-type two-body reaction [Klenovskii et al., 2013a]. The creation of KrCl* and XeI* exciplex molecules occur when a significant voltage is applied between the electrodes of exciplex sources. Within a few nanoseconds of excitation, KrCl* and XeI* exciplex molecules decompose and release UV photons at the wavelengths of 222 nm (see reactions 1.1 to 1.4) and 253 nm (see reactions 1.5 to 1.10), respectively, as follows [Ahlawat et al., 2024c] [Ahlawat et al., 2024d];

$$e^- + Kr \rightarrow Kr^+ + 2e^- \quad (1.1)$$

$$e^- + Cl_2 \rightarrow Cl + Cl^- \quad (1.2)$$

$$Kr + Cl^- + M \rightarrow KrCl^* + M \quad (1.3)$$

$$KrCl^* \rightarrow Kr + Cl + hv\ (\lambda_{peak} = 222\ nm) \quad (1.4)$$

$$e^- + Xe \rightarrow Xe^* + e^- \quad (1.5)$$

$$e^- + Xe \rightarrow Xe^+ + 2e^- \quad (1.6)$$

$$e^- + I_2 \rightarrow I + I^- \quad (1.7)$$

$$Xe^+ + I^- + M \rightarrow XeI^* + M \quad (1.8)$$

$$Xe^* + I_2 \rightarrow XeI^* + I \quad (1.9)$$

$$XeI^* \rightarrow Xe + I + hv\ (\lambda_{peak} = 253\ nm) \quad (1.10)$$

Table 1.2: Wavelengths of the principal radiative transitions in exciplex molecules and the theoretical maximum efficiency of B-X transition [He et al., 1998].

Rare gas atom (R)	**Halogen atom (x)**	**Different transition wavelength of RX* molecule (nm)**			
		$D_{1/2} \rightarrow X_{1/2}$	$B_{1/2} \rightarrow X_{1/2}(\eta)$	$C_{3/2} \rightarrow A_{3/2}$	$D_{1/2} \rightarrow A_{1/2}$
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**

When KrCl* or XeI* gas is excited within a gas gap, the resulting plasma emits UV-C photons at wavelengths of 222 nm and 253 nm, respectively. These emissions can be best utilized for different food sterilization applications, such as milk and dairy product sterilization, when generated using excimer lamps [von Woedtke et al., 2022]. Additionally, DBD plasmas also offer significant advantages for industrial use due to their simplicity, geometric flexibility, high efficiency, and cost-effectiveness [Bogaerts et al., 2002].

Accordingly, this work focuses on the design, development, and optimization of cylindrical excilamps emitting different wavelengths (222 nm and 253 nm) in the UV-C region for milk sterilization applications. The primary objective is to utilize these developed sources to evaluate microbial load reduction in milk and to investigate the impact of different wavelengths on the physicochemical properties of milk across various UV reactors.

1.4 Research Plan

1.4.1 Research Gaps in the Literature

Despite the extensive research and ongoing advancements in the field of milk sterilization, there remains a pressing need for systems that can overcome the limitations inherent in existing milk treatment methods. To improve the reliability and effectiveness of milk sterilization technology using UV and cold plasma, there exists the following research gaps:

1. The present market-based UV-C sources contain mercury, which is a highly toxic material for humans and the environment. An alternative for these sources could be plasma UV excimer light sources. Nevertheless, the excimer sources reported so far have heating issues, which make the process thermal. Therefore, there is a need to design and develop varied geometry UV excimer light sources to control the heating of such sources without any external cooling jacket.

2. Extensive research on UV-C at 254 nm for food sterilization has been done and lots of literature is available. However, the potential use of Far UV-C (222 nm) remains underexplored, particularly for milk sterilization. This presents a significant research opportunity to develop new non-thermal pasteurization methods that maintain the nutritional quality of milk. As the demand for healthier, minimally processed food products continues to grow, there is an increasing need for pasteurization alternatives that can maintain the integrity of milk's nutritional content. By exploring non-thermal pasteurization methods, such as Far UV-C and Cold plasma, we have the potential to create solutions that will not only eliminate harmful microorganisms but may also retain the overall nutritional profile of the milk.

3. Plasma technology presents a promising advancement in the field of milk sterilization, offering a potential alternative to traditional methods. However, the current techniques still face significant limitations, particularly in their inability to precisely control the changes in pH and conductivity that occur during the process. These parameters are essential for preserving the natural quality of milk, as even slight alterations can affect its taste, nutritional value, and shelf life. Without a detailed understanding and regulation of these variables, the full potential of plasma sterilization cannot be realized. Therefore, addressing some of these gaps by developing more refined control mechanisms for pH and conductivity could greatly enhance the precision and efficiency of plasma-based sterilization methods, ensuring that the milk maintains its desired characteristics while benefiting from the advanced sterilization capabilities plasma technology offers.

4. Traditional milk treatment systems often face significant challenges related to cleaning and operational efficiency. These systems typically require multiple cleaning passes to achieve the desired level of microbial reduction, which leads to extended processing times and higher operational costs. The inefficiencies of these conventional methods are not only time-consuming but also contribute to unnecessary resource consumption, such as chemicals, water and energy, which further adds to the environmental and financial burden. To address these issues, there is a growing need within the dairy industry for the development of more effective and efficient systems. A streamlined solution that integrates non-thermal sterilization techniques could greatly improve the cleaning process. These advanced technologies would not only ensure better microbial control but also significantly reduce the need for repeated cleaning cycles. By adopting non-thermal sterilization methods, the industry could benefit from faster, more energy-efficient processes, while enhancing the overall sustainability of milk treatment. Therefore, developing a streamlined, easy-to-clean system that leverages non-thermal sterilization techniques represents a critical need in the milk industry.

1.4.2 Formulation of Research Objectives

1. To develop DBD plasma-based mercury-free 222 nm and 253 nm exciplex light sources for the efficient production of UV-C irradiation and utilize these sources for milk sterilization.

2. To compare the efficiency of 222 nm and 253 nm UV-C radiations in milk sterilization with conventional pasteurization processes.

3. To develop a DBD-based cold plasma device for milk sterilization and to optimize it on the basis of input parameters and study its impact on the physicochemical properties of raw milk.

4. To develop a small-scale annular flow reactor that ensures optimal exposure time of UV radiation for milk sterilization, and is capable of efficiently and uniformly treating milk. By fine-tuning the reactor's geometry and flow dynamics, we seek to achieve precise control over the UV exposure, thereby improving the sterilization process and enabling effective pilot testing.

1.4.3 Thesis Outlines

This research utilizes standardized experimental techniques to achieve the objectives outlined in the objective of the thesis. It provides a detailed overview of the methodology and experiments conducted, followed by an analysis and discussion of the resulting data. The thesis concludes with a summary of the key findings and offers recommendations for future research particularly on Far UV-C Excimer sources in milk sterilization.

The thesis is majorly divided into two parts. The first part explains the development and characterization of 222 nm and 253 nm 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 milk sterilization, particularly to check the microbial inactivation efficiency in milk and its impact on the MBRT & physicochemical properties of the milk. The content is divided into 6 chapters, including the first chapter which provides an introduction to UV disinfection and the newly developed far UV-C excilamp technology for food sterilization applications.

Chapter 1 also presents a comprehensive examination of the principles, applications, and difficulties associated with the sterilization of food items using UV technology. The importance of utilizing Far UV-C in the milk sterilization is clearly brought in and discussed in detail in this chapter. In addition, the existence of a knowledge gaps in the context of the thesis are also discussed, and accordingly the research objectives are set to address the knowledge gaps. The remaining chapters in this thesis are structured as follows.

Chapter 2: This chapter describes the different experimental and diagnostic techniques used for excilamps manufacturing and characterization. A brief introduction of the irradiation technique is described. The details of instruments and methods used to check the physical and chemical properties of the milk are also elaborated in this chapter.

Chapter 3: In this chapter, detailed studies on the development of the KrCl* and XeI* 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.