

Declaration

I hereby declare that the work presented in this Thesis titled *Cold Sterilization Studies using UV Irradiation and DBD Plasma to Supplement the Current Techniques for Milk Preservation* submitted to the Indian Institute of Technology Jodhpur in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Prof. Ram Prakash. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.



Vigyan Gadodia
P19PH019

Certificate

This is to certify that the thesis titled *Cold Sterilization Studies using UV Irradiation and DBD Plasma to Supplement the Current Techniques for Milk Preservation*, submitted by *Vigyan Gadodia (P19PH019)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

A handwritten signature in blue ink, appearing to read 'Ram Prakash', with a horizontal line extending from the end.

Ram Prakash
Ph.D. Thesis Supervisor

Abstract

Milk, one of the most complete nutrition mixes for human consumption, also presents itself as the most potent nutrient medium for bacterial growth. This becomes especially pronounced for a hot country like India with highly fragmented milk production, spoiling the milk before it reaches processing plants. In recent years, the search for less expensive alternatives to cold chain preservation and heat-based shelf-life improvement has intensified. Hence, the study of the impact of Ultraviolet (UV) radiation and plasma on the physicochemical properties of various substances, including milk, has gained prominence. UV-C (200–280 nm) is also well-known for inactivating various bacteria and spores in the aqueous solution based on its DNA absorption capacity. However, the hazardous impact of conventional UV lamps on individuals and the environment due to the presence of mercury limits their usage for sterilization purposes. Far UV-C (222 nm) treatment has emerged as a potential method to replace conventional 254 nm low-pressure mercury UV-C lamps to ensure the microbiological safety of food items.

In this thesis, research focuses on utilizing dielectric barrier discharge (DBD) plasma sources and DBD based mercury-free 222 nm and 253 nm exciplex sources to investigate the microbial and physicochemical properties of milk. In the first study, we demonstrate a DBD based mercury-free 222 nm exciplex source and compare it with 253 nm and pasteurization methods. The UV dose delivered to the milk samples has been estimated using the chemical actinometry method and found to be 10.9 J/ml. The methylene blue reduction test (MBRT) of milk has been increased more than 5 h, within just 2.5 min of far UV-C treatment. Approximately 2.6 log and 2.1 log decrease in the *E. coli* and *S. aureus* have been achieved after 2.5 minutes of 222 nm treatment of whole milk. We infer that 222 nm UV light is more efficacious vis-à-vis 253 nm and pasteurization in increasing milk quality without altering its physicochemical properties, indicating its potential use as a more efficient sterilizing source for enhancing milk safety, quality, and shelf life.

In a further study, we have focused on designing a continuous milk treatment annular UV reactor. The MBRT of milk has again increased more than 5 hours, within just four passes through the UV reactor. Approximately 5 log reductions in the *Salmonella typhimurium* and *S. aureus* have been achieved in three passes of whole milk. We found that the proposed UV reactor has an identical performance in inactivating the microorganisms compared to pasteurization without altering its physicochemical properties.

In another study, an effort has been made to design a DBD based large volume surface plasma discharge system for direct treatment of milk. The developed system is optimized for operational parameters, and raw milk has been treated at different time intervals. The pH and color characteristics of raw milk samples have not been affected by the proposed cold plasma treatment. Nevertheless, the conductivity of the milk significantly increases with presence of charged ions assisting reduction of harmful bacteria in the milk. After continuous operation of the system for more than 30 minutes, there was no significant change in the raw milk temperature, which is a key requirement for milk decontamination without milk heating up using a cold plasma treatment in the developed DBD geometry.

This thesis presents a promising potential for the use of mercury-free far UV-C irradiation as a viable and non-thermal technology in the dairy industry, food sector, and overall sterilization applications. It highlights the capabilities of dielectric barrier discharge based cold plasmas to enhance milk safety, quality, and shelf-life, presenting a more efficient alternative for improving these aspects compared to traditional methods.

List of Publications

Research Articles

1. **Gadodia V**, Ahlawat K, Jangra R et al. (2024) Potential use of DBD based 222 nm exciplex light source for milk sterilization and its comparative analysis with 253 nm UV-light and conventional pasteurization. **Journal of Food Measurement and Characterization** 18 1-12.
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4. Ahlawat K, Jangra R, **Gadodia V**, Prakash R, “DBD-Based Planar 222 nm Kr/Cl₂ Excilamps: Effective for Surface Sterilization” presented **Flash talk and Poster** at **10th PSSI - Plasma Scholars Colloquium (PSC-2024)**, from 4-6 July, 2024 held at IIT Delhi, India.

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List of Symbols

<i>Symbol</i>	<i>Description</i>
eV	Electron Volt
$^{\circ}C$	Degree Celsius
K	Kelvin
$\%$	Percentage
Hz	Hertz
kHz	Kilo-hertz
MHz	Mega-hertz
nm	Nanometer
μm	Micro-meter
mm	Millimeter
cm	Centimeter
m	Meter
W	Watt
V	Volt
kV	Kilo-volt
ft	Feet
ns	Nanosecond
s	Seconds
min	Minutes
h	Hour
C	Coulomb
μ_e	Electron Mobility
ml	Milliliter
L	Liter
g	Gram
mg	Milligram
θ	Diffraction Angle
d	Lattice Spacing
λ	Wavelength
$\text{\AA}$	Angstrom
k	First-order Reaction Rate Constant
A	Ampere
mA	Milli-ampere
μM	Micro-molar
mM	Milli-molar
M	Molar
kb	Kilo-byte
C	Capacitance
f	Frequency
J	Joule

List of Abbreviations

<i>Abbreviation</i>	<i>Full form</i>
UV	Ultraviolet
DNA	Deoxyribonucleic Acid
RNA	Ribonucleic Acid
VUV	Vacuum Ultraviolet
DBD	Dielectric Barrier Discharge
LED	Light Emitting Diodes
AC	Alternating Current
VDBD	Volume Dielectric Barrier Discharge
SDBD	Surface Dielectric Barrier Discharge
LP	Low Pressure
Kr	Krypton
Cl ₂	Chlorine
KrCl*	Krypton Chlorine Exciplex
RF	Radio Frequency
FWHM	Full Width Half Maxima
SARS	Sever Acute Respiratory Diseases
H ₂ O ₂	Hydrogen Peroxide
O ₃	Ozone
DP	Direct Photolysis
LPUV	Low Pressure Ultraviolet
MPUV	Medium Pressure Ultraviolet
•OH	Hydroxyl Radical
NTP	Non thermal Plasma
RONs	Reactive Oxygen and Nitrogen Species
NO ₃	Nitrates
NO ₂	Nitrites
XeI*	Xenon Iodide Exciplex
DDBD	Double Dielectric Barrier Discharge
E _{EO}	Electrical Energy per Order
FTIR	Fourier Infrared Spectroscopy
VD	Volume Discharge
PMT	Photomultiplier Tube
OES	Optical Emission Spectroscopy
CFU	Colony Forming Units
LB	Luria Bertani
HRTEM	High Resolution Tunnelling Electron Microscopy
XPS	X-ray Photoelectron Spectroscopy
XRD	X-Ray Diffractometer
PTW	Plasma Treated Water
HV	High Voltage
MBRT	Methylene Blue Reduction Test
WF	Water Factor
PF	Petri Factor
DF	Divergence Factor
RF	Reflection Factor