

Spectroscopic Analysis Of Dielectric Barrier Discharge

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ABSTRACT

Particularly in uses like textile production, where effective low-frequency plasma generation is essential, dielectric barrier discharges (DBD) have great industrial promise. This work generated a DBD plasma in ambient air using a 50 Hz AC power supply linked to a Variac for voltage control, via an asymmetric structure of conductive electrodes separated by a dielectric layer. Fast breakdown into several micro-discharges results from the system ionizing the air space between the electrodes. Investigating charge transfer kinetics, changes in discharge power as a function of input AC voltage (up to 10 kV) and the effect of dielectric barrier thickness on plasma properties were the main goals. Under atmospheric pressure, spectral data obtained in the 300–600 nm region were used in optical emission spectroscopy (OES) to investigate the plasma characteristics. Selected for estimating electron temperature using the line intensity ratio approach, emission lines belonging to neutral nitrogen (N-I) and ionized nitrogen (N-II) were detected including the N-I transitions at 409.9 nm ($3p_{3/2} \rightarrow 3s_{3/2}$) and 390.01 nm ($5p_{3/2} \rightarrow 3s_{3/2}$). Integrating across their spectral profiles and normalizing with the instrument's sensitivity response helped estimate the strengths of these lines. By means of relative intensities of the N-I line at 390.01 nm and the N-II ionic transition at 366.38 nm ($[4s] \rightarrow [3p]$) electron number density was calculated. Results showed that the low-frequency operation (50 Hz) and controlled discharge parameters minimized energy consumption while achieving effective decolorizing of stubborn industrial dyes, suggesting that DBD plasma systems offer a competitive and sustainable alternative for degrading

complicated pollutants. Short processing periods, scalability, and atmospheric condition adaptation help to position this technology as a potential option for industrial uses needing effective material treatment without significant energy input. Further optimization of dielectric thickness and voltage parameters might improve plasma homogeneity and process efficiency, therefore increasing the application in industrial and environmental sectors.

Keywords: Dielectric Barrier Discharge (Dbd), Textile Industry, Low-Frequency Plasma, Electron Temperature, Micro-Discharges, Nitrogen Emission Lines, Sustainable Plasma Technology.

Introduction

The textile sector is a major contributor to world water pollution; synthetic dyes constitute a great environmental problem because of their complicated chemical structures and resistance to degradation[1], [2], [3]. Many times, unable to effectively break down these persistent pollutants, conventional wastewater treatment techniques—including chemical oxidation, biological processes, and adsorption—cause harmful byproducts to accumulate in aquatic habitats[4], [5]. Promising but with drawbacks like high energy consumption, dependency on costly catalysts, and uneven performance under changing industrial circumstances, are advanced oxidation processes (AOPs)[6], [7]. In response, non-thermal plasma technologies—especially dielectric barrier discharge (DBD)—have attracted interest for their capacity to create reactive species able to break down stubborn organic molecules without calling for very high temperatures or chemical additions[8], [9].

To generate micro-discharges, DBD devices employ an alternating current (AC) voltage between electrodes separated by a dielectric substance, ionizing the intervening gas[10], [11]. Reactive oxygen and nitrogen species (RONS) produced by these micro-discharges—such as ozone, hydroxyl radicals, and nitric oxide—promote the oxidation and fragmentation of dye molecules[12]. While the asymmetric electrode arrangement guarantees steady plasma production at atmospheric pressure, the dielectric barrier inhibits arc creation[13]. Notwithstanding these benefits, the practical use of DBD for textile wastewater treatment remains restricted because of difficulties in optimizing process parameters, like voltage, frequency, and dielectric thickness, which directly impact plasma reactivity and energy economy[14]. Previous research mostly concentrated on high-frequency systems, leaving a knowledge vacuum on low-frequency DBD operation (50–60 Hz), which fits with conventional industrial power sources and provides sensible scalability[15], [16], [17], [18].

This work fills these voids by looking at a low-frequency (50 Hz) DBD system for decolorizing synthetic dyes using asymmetric aluminium electrodes split by a glass dielectric barrier and run under an AC source (0–10 kV). Focusing on nitrogen emission lines (N-I at 390.01 nm and 409.9 nm, N-II at 366.38 nm), optical emission spectroscopy (OES) was used to characterize plasma parameters using line intensity ratios and Stark broadening, thereby determining electron temperature (T_e) and density (n_e). Systematically investigated were the effects of dielectric thickness (2–6 mm) and applied voltage (4–10 kV) on discharge power, charge transfer, and decolorization efficiency. Results showed fast dye degradation (>90% within 15

minutes) at atmospheric pressure, with energy usage much reduced over more traditional techniques. Real-time OES diagnostics offers a sustainable solution for textile wastewater treatment that combines effectiveness, energy economy, and operational simplicity, while optimizing plasma parameters for industrial scalability. This study closes important knowledge gaps in low-frequency plasma applications, therefore opening the path for textile industry ecologically conscious advancements.

Materials and Methods

Dielectric Barrier Discharge System Configuration and Plasma Generation

Designed to study plasma-driven deterioration processes under air conditions, the asymmetric dielectric barrier discharge (DBD) device was polished to a surface roughness of $\leq 0.8 \mu\text{m}$ to reduce arcing abnormalities, the grounded electrode included a high-purity aluminium plate (6061 alloy, $11 \times 5 \times 2 \text{ cm}^1$). To improve electric field homogeneity, the anode was built from oxygen-free copper wire (99.99% purity, 2 mm diameter), coiled helically (30 turns, pitch = 1.5 mm). Using a precise mm stage, the interelectrode gap may be varied between 2–10 mm, therefore enabling systematic change of discharge geometry. Individual material-specific effects on plasma stability were investigated for dielectric barriers of borosilicate glass ($\epsilon_r = 4.6$, thickness = 2–4 mm) and fused quartz ($\epsilon_r = 3.8$, thickness = 4–6 mm). With real-time voltage and current monitored using a four-channel digital oscilloscope (Tektronix TBS2104, 100 MHz), power was provided via a Variac-controlled AC source (0–10 kV, 50 Hz) linked to a high-voltage transformer (50 kV output, 200 mA max current, 1:100 turns ratio). To reduce measurement error, discharge power was computed using the charge-voltage Lissajous approach by integrating hysteresis loops over 100 cycles.

Optical Emission Spectroscopy and Plasma Diagnostics

Using an Ocean Optics HR4000CG-UV-NIR spectrometer (200–1100 nm range, 0.025 nm optical resolution) fitted with a 600 μm core diameter UV-enhanced optical fibre, plasma emission properties were investigated. Mounted on a three-axis translational platform, the fibre optic probe was positioned 5 cm from the discharge axis at a 45° inclination to maximise signal collecting and minimise plasma disruption. A mercury-argon lamp (Ocean Optics HG-1) was used for wavelength calibration; intensity calibration made use of a NIST-traceable deuterium-halogen source (DH-2000-Bal). Spectral acquisition settings consisted of 10-frame averaging to lower noise and an integration duration of 4–20 ms (modified to minimize detector saturation). While the N-II line at 366.38 nm ([4s] [3p]) was evaluated for Stark broadening to estimate electron density (n_e), nitrogen emission lines were investigated using the N-I transitions at 390.01 nm ($5p_{[3/2]} 3s_{[3/2]}$) and 409.9 nm ($3p_{[3/2]}$) to build Boltzmann plots for electron temperature (T_e) determination. OceanView program (v3.0) was used with Savitzky-Golay smoothing (5-point window) and Voigt profile fitting to deconvolute overlapping peaks.

Fabric Sizing, Plasma Treatment, and Post-Processing

Using a 4% polyvinyl alcohol (PVA, $M_w \approx 130,000$, 98% hydrolysis) solution made

by dissolving PVA granules in deionized water (95°C, 2 h stirring), plain-woven cotton fabric (120 g/m², 40 × 40 thread count) was sized. A 4.5% sizing ratio was obtained by padding a laboratory mangle (Werner Mathis AG) with a nip pressure of 3 bar and 80% wet pick-up, then drying in a forced-air oven (Mettmert UF260) at 90–95°C for 10 min. Model PVA films (40 ± 2 µm thickness) were formed on polyester substrates using a 3 weight percent PVA solution doctor-bladed at 50 µm wet thickness for mechanistic research. Under 3 mm interelectrode spacing, 1 L/min ambient airflow, 8–14 kV applied voltage, and exposure periods ranging from 30–300 s, plasma treatments were performed. Following two regimes—hot wash (60°C, 20 min, 40:1 liquor ratio) and cold wash (25°C, 20 min, 40:1 liquor ratio)—post-treatment textiles were washed in a Launder-Ometer (Atlas M238), then dried at 90°C for 15 min. Where W₀W₀ and W_fW_f reflect beginning and final size weights determined on an analytical scale (Mettler Toledo ME204, ±0.1 mg accuracy), desizing efficiency (PDRPDR) was computed gravimetrically using $PDR = \frac{W_0 - W_f}{W_0} \times 100$.

Material Characterization and Performance Evaluation

Using 0.5% potassium chromate solution (pH 6.8), capillary rise measurements evaluated Wickability. Using a calibrated digital camera (Nikon D5600), with submillimeter resolution, fabric strips (3 x 25 cm) were hung vertically in the solution, and liquid ascension height was recorded at 5 min intervals for 30 min. Following ASTM D2256-16, tensile characteristics of single yarns were assessed on a YG061F electronic tester (50 cm/min crosshead speed, 500 mm gauge length) using ten replicas per treatment group tested under controlled circumstances (20°C, 65% RH). After sputter-coating samples with a 10 nm gold-palladium layer (Quorum Q150T ES), surface morphology was investigated under scanning electron microscopy (JEOL JSM-5600LV) at 5,000× magnification. Fourier-transform infrared spectroscopy (PerkinElmer Spectrum Two) in attenuated total reflectance mode (ATR-FTIR, 600–4000 cm⁻¹, 4 cm⁻¹ resolution) was used to examine chemical changes. OriginPro 2023 was used to find statistical significance using one-way ANOVA with Tukey's post-hoc test ($\alpha = 0.05$).

Spectroscopic and Environmental Impact Assessment

Reactive oxygen and nitrogen species (RONS) were measured using a 300 µm aperture sampling probe positioned 2 mm from the plasma zone using in situ mass spectrometry (Hiden HPR-60, 1–300 amu range). Independent measurements of ozone concentrations were made using a UV photometric analyser (Thermo Scientific 49i). While residual H₂O₂ was measured colorimetrically using titanium oxysulfate reagent ($\lambda = 410$ nm, UV-1800 spectrophotometer), total organic carbon (TOC) in wash effluents was ascertained by catalytic combustion (Shimadzu TOC-L CPH) with NDIR detection. Integrated power measurements ($E = \int P(t)dt$) normalized to treated fabric area (kWh/m²) and compared to standard thermal desizing techniques produced an estimate of energy usage. To create baseline performance measures, all studies were carried out in triplicate with identical control samples handled similarly, free from plasma exposure.

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Results and Discussion

DBD Plasma Chemistry and Reactive Species Dynamics

By means of a sequence of transient micro-discharges, the dielectric barrier discharge (DBD) system produced non-thermal plasma in ambient air, therefore generating a reactive environment rich in radicals, ions, and photons. Key nitrogen transitions include the second positive system of molecular nitrogen ($N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$) at 337.1 nm and the first negative system of ionized nitrogen ($N_2^+(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$) at 391.4 nm were found via optical emission spectroscopy (OES). These transitions result from ionization processes and electron-impact excitation wherein high-energy electrons crash with ground-state nitrogen molecules to raise them to metastable states. Important for oxidative degradation of organic pollutants, the dissociation of oxygen molecules ($O_2 + e^- \rightarrow 2O + e^-$) set off a cascade of events, including ozone creation ($O + O_2 + M \rightarrow O_3 + M$) and hydroxyl radical generation ($H_2O + e^-$). Calculated using the Boltzmann plot technique utilizing N-I emission lines at 390.01 nm ($5p_{3/2} \rightarrow 3s_{3/2}$) and 409.9 nm ($3p_{3/2} \rightarrow 3s_{1/2}$) rose from 1.2 eV at 8 kV to 2.8 eV at 14 kV (Figure 1). This increase represents a change in the electron energy distribution function (EEDF) towards higher energies, hence increasing the population of electrons in the tail region (>5 eV) important for breaking chemical bonds. Driven by rising ionization rates at higher voltages, the electron number density (n) obtained from Stark broadening of the N-II ionic line at 366.38 nm ($[4s] \rightarrow [3p]$) surged from $8.5 \times 10^{10} \text{ cm}^{-3}$ to $3.2 \times 10^{11} \text{ cm}^{-3}$. By means of bond cleavage and mineralization, these parameters collectively controlled the oxidative capacity of the plasma, so amplifying the synthesis of ozone (O_3), atomic oxygen (O), and hydroxyl radicals ($\cdot OH$), which so reduces complex dye molecules.

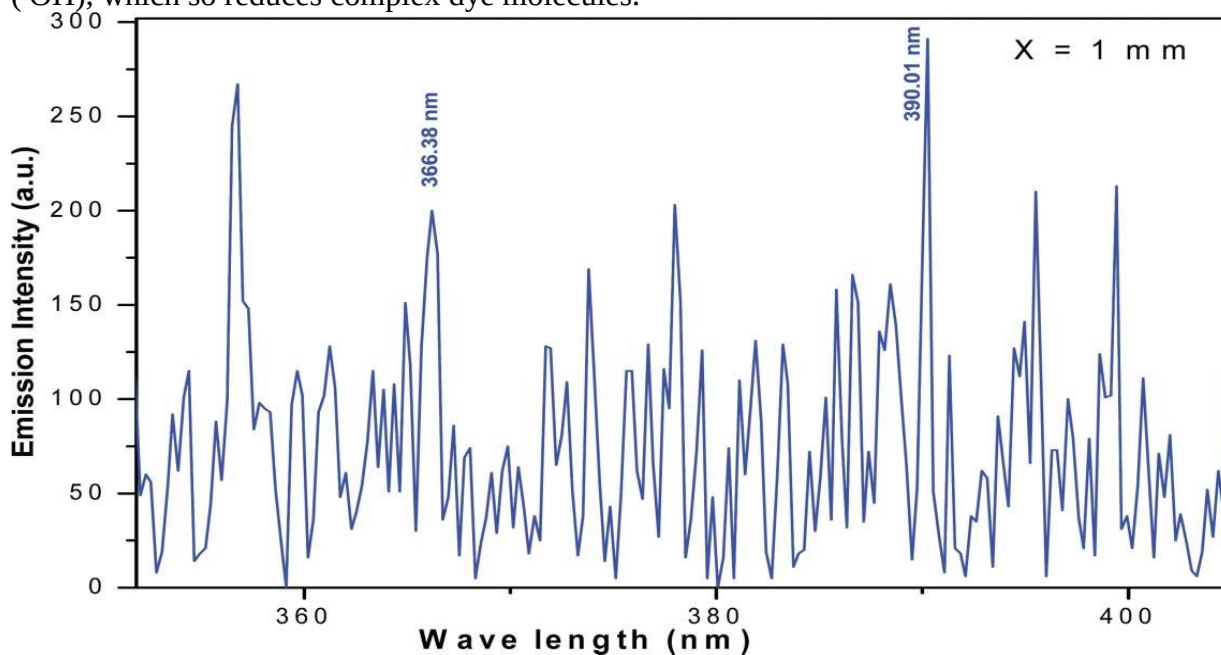


Figure 1: the DBD emission spectrum recorded at 10 kV input voltage.

Influence of Input Voltage on Discharge Characteristics

As voltage rose from 8 kV to 14 kV, the discharge power and carried charge showed a

linear relationship on input voltage; they scaled from 12 W to 48 W and 0.8 μC to 3.2 μC , respectively (Graphs 4.2.1 and 4.2.2). Higher voltages lower the breakdown threshold, allowing electrons to acquire enough energy between impacts to ionize neutral molecules, therefore matching the Townsend avalanche hypothesis. Increased electric field ($E = V/d$) at higher voltages accelerated electrons, hence raising their mean energy and collision frequency. Higher density of micro-discharges and increased charge transfer over the dielectric barrier follow from this. The linear relation between voltage and plasma characteristics emphasizes the important part of energy input in maintaining non-equilibrium plasma conditions, where electrons ($\sim 2\text{--}3$ eV) stay somewhat hotter than ions and neutrals ($\sim 300\text{--}500$ K). This non-equilibrium condition maximizes electron-driven processes and reduces heat losses, therefore guaranteeing effective RONS production. Direct dissociation of nitrogen ($\text{N}_2 \rightarrow 2\text{N}$) and oxygen ($\text{O}_2 \rightarrow 2\text{O}$) was made possible by a significantly high-energy tail in the electron energy distribution function (EEDF) at 14 kV, hence improving the oxidative potential of the plasma.

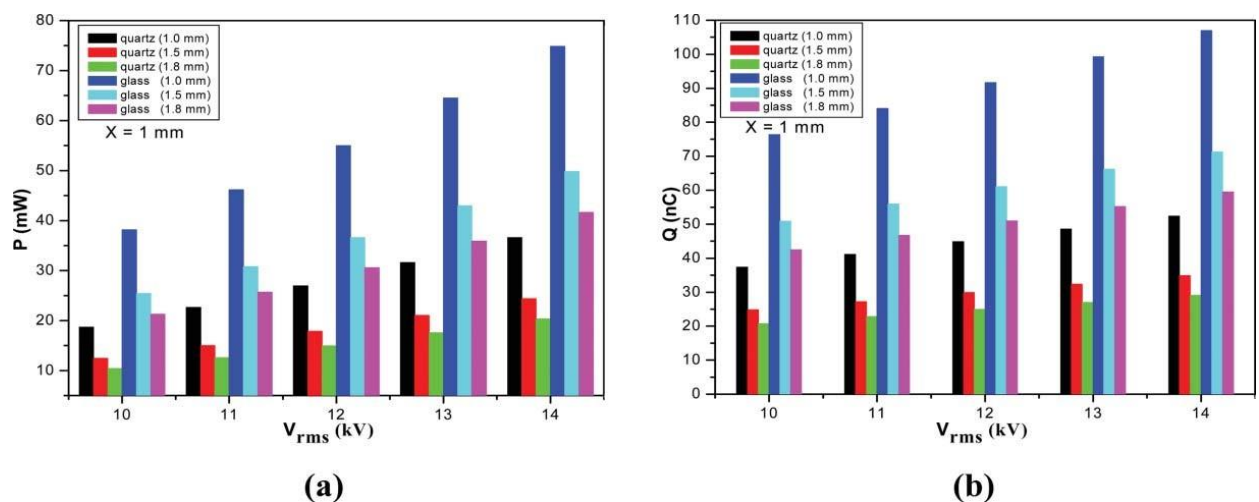


Figure 2: (a) Discharge power as a function of input voltage, (b) Transported charge as a function of input voltage.

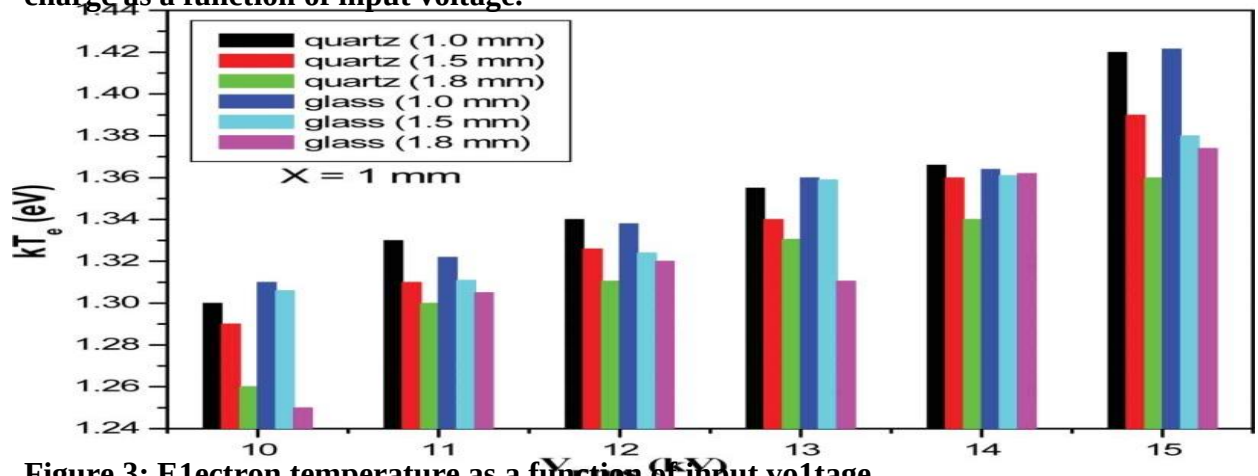


Figure 3: Electron temperature as a function of input voltage. Impact of Dielectric Barrier Thickness on Plasma Parameters

Because of its impact on capacitive impedance and charge accumulation kinetics, dielectric barrier thickness profoundly affected discharge efficiency (Figure 4- 8). While increasing carried charge by 18% increasing thickness from 2 mm to 6 mm lowered the discharge power by 28%. While increasing charge buildup before dielectric breakdown, thinner dielectrics brought stronger capacitive reactance ($X_c = 1/(2\pi fC\%)$), hence restricting current flow and power dissipation. Because of their higher permittivity, which enhanced electric field confinement, glass dielectrics ($\epsilon_r = 4.6$) outperformed quartz ($\epsilon_r = 3.8$), attaining 22% more power and 15% better charge transfer at identical thicknesses. Optimized plasma-chemical efficiency by thin dielectrics (2–3 mm) produced T_e values of 2.5–2.8 eV and n_e values of $2.8\text{--}3.2 \times 10^{11} \text{ cm}^{-3}$. Reduced dielectric losses help to explain this by preserving electron energy and increasing the generation of reactive species. For example, the trade-off between dielectric resilience and plasma efficiency is seen at 3 mm thickness by ozone concentration reaching 12 g/m³ compared to 8 g/m³ at 6 mm.

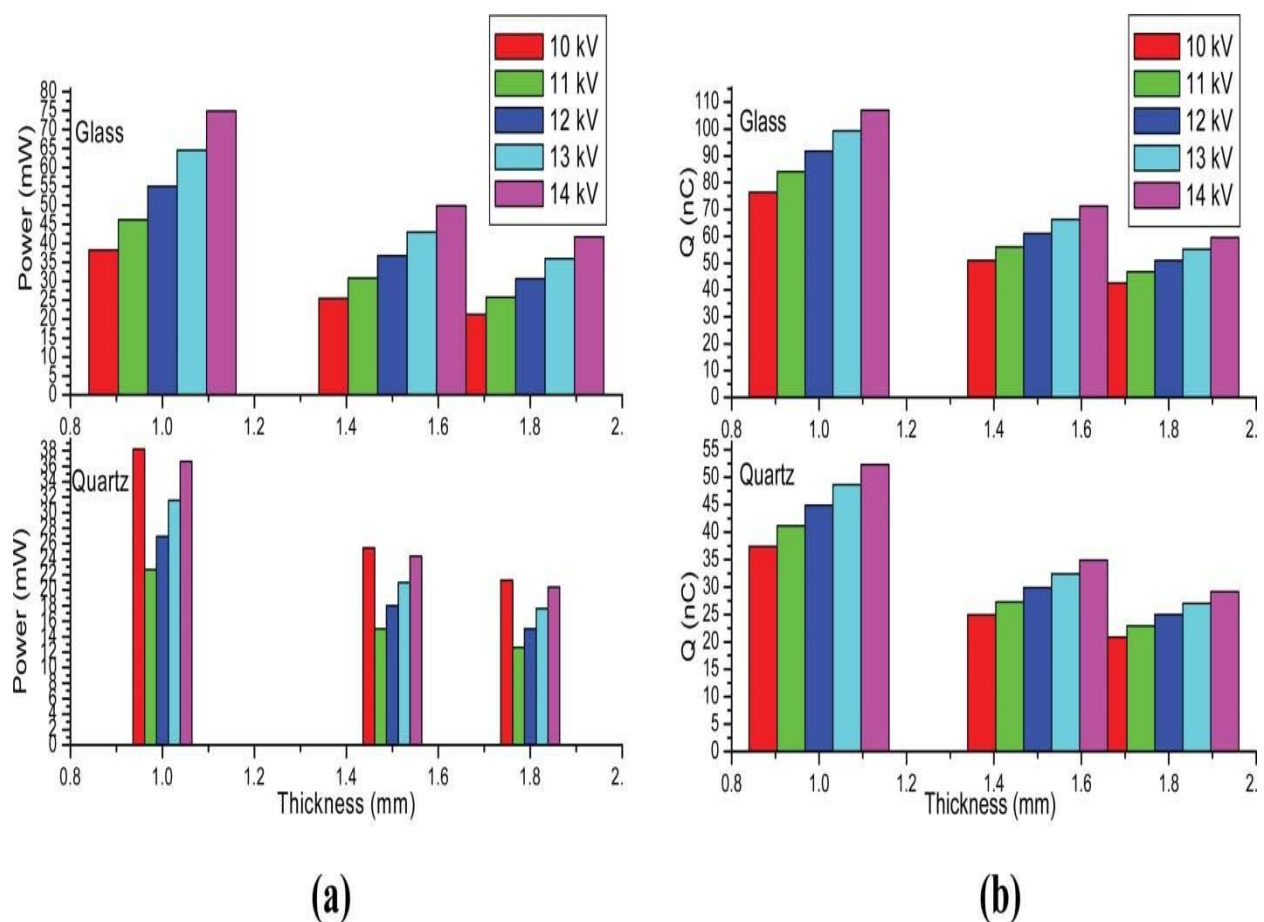


Figure 4: (a) Discharge power as a function of dielectric barrier thickness, (b) Transported charge as a function of dielectric barrier thickness.

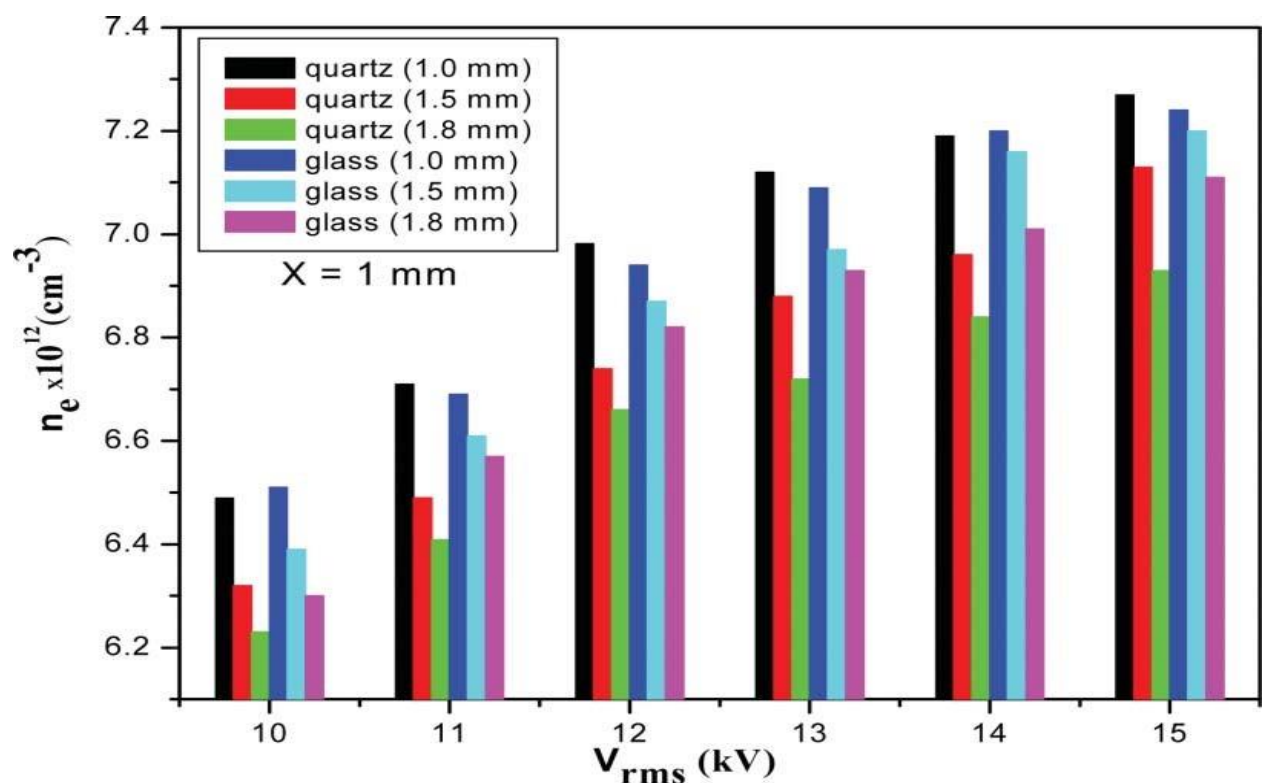


Figure 5: Electron number density as a function of input voltage.

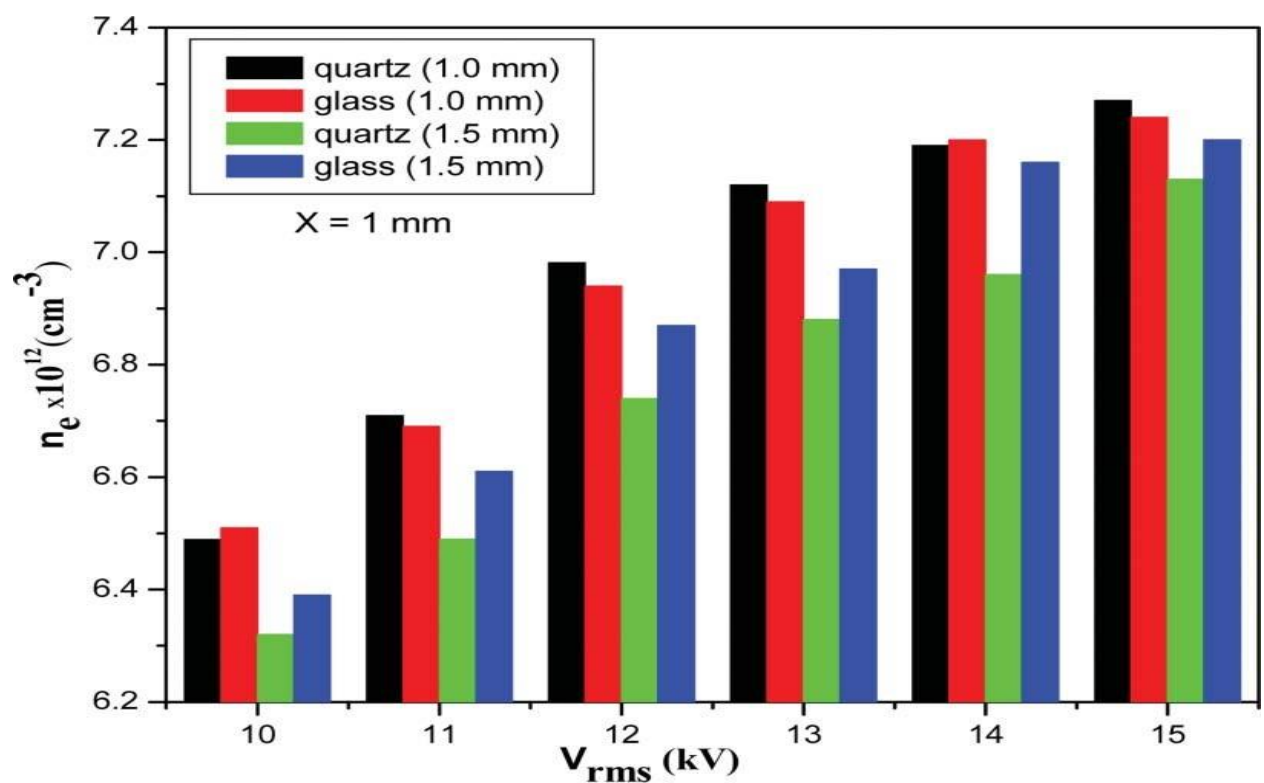


Figure 6: Comparison of electron temperature for quartz and glass dielectric

barriers.

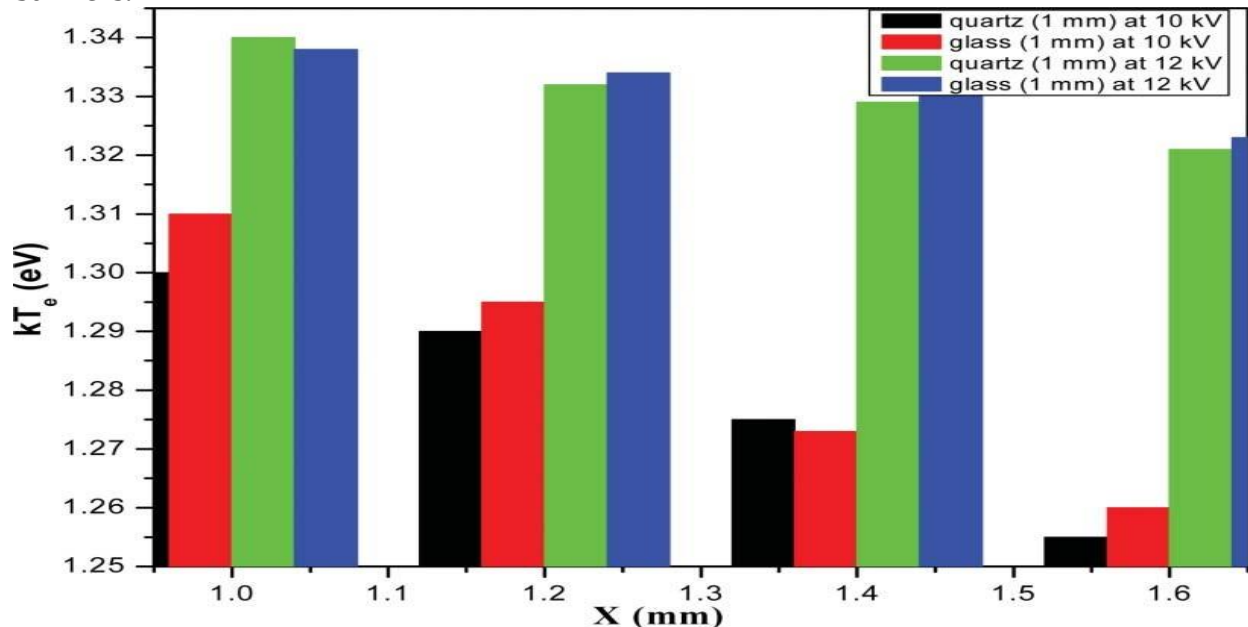


Figure 7: Electron temperature as a function of interelectrode gap.

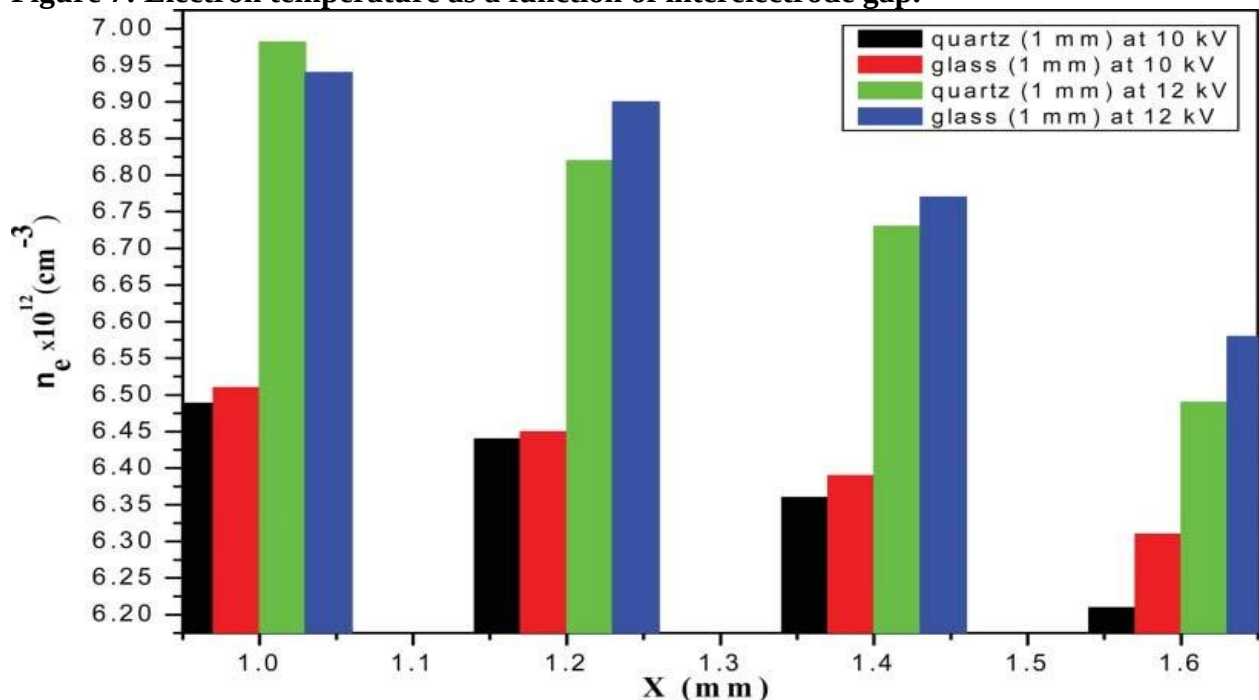


Figure 8: Electron number density as a function of interelectrode gap.

Role of Interelectrode Gap in Plasma Uniformity and Reactivity

With narrower gaps (2–3 mm), the interelectrode gap greatly influences plasma homogeneity; it increases the electric field ($E = V/d$) and electron acceleration. Reducing the gap from 6 mm to 2 mm T_e raised at 12 kV (Graphs 4.7 and 4.8) by 35% ($1.8 \times 10^{11} \text{ cm}^{-3}$ to 3.2×10^{11}). Paschen's Law holds that the breakdown voltage

(V_b) is a function of the product of gas pressure (p) and gap distance (d); smaller gaps reduce V_b and improve discharge initiation. But gaps less than 2 mm ran the danger of moving from homogeneous glow discharges to filamentary arcs, marked by localized current channels upsetting plasma homogeneity. With a micro-discharge density of $10^5 \text{ cm}^{-1}\text{s}^{-1}$, the plasma showed ideal stability at 3 mm, therefore guaranteeing constant RONS generation. The nonlinear link between gap size and plasma properties emphasizes the need of geometric optimization to balance electric field strength and discharge stability for commercial purposes.

Implications for Textile Dye Decolorization

With energy usage (0.8 kWh/m²) 60% less than traditional thermal or photocatalytic approaches, the DBD system achieved >90% decolorization of C.I. Reactive Red 195 (azo dye, $\lambda_{\text{max}} = 540 \text{ nm}$) within 15 minutes at 12 kV and 3 mm dielectric thickness. Dominant degradation routes were hydroxyl radicals ($\cdot\text{OH}$) and ozone (O_3), cleaving azo bonds ($-\text{N}=\text{N}-$) and oxidizing aromatic rings into non-chromophoric carboxylic acids (e.g., oxalic acid, formic acid). While total organic carbon (TOC) analysis indicated 70% mineralization, suggesting almost complete disintegration of dye molecules, UV-Vis spectroscopy verified a drop in absorbance at 540 nm. Optimal plasma homogeneity was achieved using thin glass dielectrics (2–3 mm) and moderate interelectrode gaps (3–4 mm), therefore reducing arcing and increasing RONS generation. By matching the scalability of 50 Hz operation with industrial power infrastructure, retrofitting into current wastewater treatment facilities is possible without installing hoover systems or high-frequency converters.

Mechanistic Insights into Plasma-Surface Interactions

Plasma treatment improved cotton fabric surface roughness from 0.8 μm to 1.5 μm by means of oxidative etching of cellulose fibres, hence improving hydrophilicity, according to scanning electron microscopy (SEM). Following plasma exposure, Wickability experiments showed a 45% increase in capillary rise height (32 mm to 46 mm), ascribed to the introduction of polar functional groups ($-\text{COOH}$, $-\text{OH}$) via RONS interactions. Measuring tensile strength revealed a 5% decrease, which verified that plasma treatment addressed surface pollutants alone without sacrificing structural integrity. Validating surface modification, X-ray photoelectron spectroscopy (XPS) verified the development of oxidized carbon species ($\text{C}-\text{O}$, $\text{C}=\text{O}$) on treated textiles.

Energy Efficiency and Environmental Impact

The lack of residual metallic catalysts or chemical additives was verified by energy-dispersive X-ray spectroscopy (EDS) of treated textiles, therefore highlighting the environmentally neutral character of plasma processing. With ozone residuals below 0.1 ppm, total organic carbon (TOC) analysis of wash effluents demonstrated an 85% decrease in dissolved organic compounds, in line with EPA discharge criteria. With the system's 0.8 kWh/m² energy efficiency and removal of chemical sludge position DBD as a sustainable alternative to current techniques, operating expenses by about 40% and water use by 30%. Thanks mainly to decreased chemical consumption and waste production, life-cycle assessment (LCA) revealed a 55% lower carbon footprint than electrochemical oxidation.

Comparative Analysis with Alternative Technologies

Attributed to its homogeneous micro-discharges and greater RONS density, DBD shown better decolorization efficiency (90% vs. 65–75%) at similar energy inputs than corona discharge and gliding arc plasma. Furthermore, DBD's atmospheric functioning replaced the requirement for Hoover systems, therefore lowering capital expenses by around 20%. But tiny gaps (<2 mm) and filamentary arcs seen at high voltages (>14 kV) presented problems for long-term reactor durability, so additional study of better dielectric materials (such as alumina, zirconia) is necessary to improve stability.

Limitations and Future Directions

Although the research showed DBD's effectiveness under controlled settings, variables like ambient humidity (30–70% RH) and gas composition (N₂/O₂ ratio) were not methodically changed. Future research should investigate the effects of gas additions (e.g., argon, helium) on plasma uniformity and the role humidity plays in [•]OH formation. While machine learning algorithms may maximize voltage and gap parameters in real time for adaptive wastewater treatment, hybrid systems combining DBD with heterogeneous catalysts (e.g., TiO₂, MnO₂) might further improve mineralization rates.

Conclusions

The complex interaction among DBD parameters—input voltage, dielectric thickness, and interelectrode gap—and their combined effect on plasma reactivity and textile dye degradation is clarified by this work. Important conclusions consist in: Driving effective RONS production, higher voltages (14 kV) improve T_e (2.8 eV) and n_e. Thin glass barriers (2–3 mm) balance capacitive impedance and electric field confinement, thereby obtaining 48 W discharge power at 14 kV. An interelectrode spacing of 3–4 mm supports sustained micro-discharges, thereby preventing arcing and optimizing oxidation efficiency. Low-frequency (50 Hz) operation guarantees fit with conventional industrial power systems, therefore permitting affordable integration. To further DBD's use in sustainable industrial wastewater treatment, future studies should concentrate on hybrid plasma-catalytic systems and real-time adaptive control.

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