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Review Article

A Comprehensive Review on Dielectric Barrier Discharge (DBD)

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ABSTRACT

Here, a review of the process of dielectric barrier discharge (DBD) and its applications is conducted. Dielectric-barrier discharges, often known as silent discharges or inaudible discharges, are non-equilibrium discharges that are easily controlled throughout a large range of pressure and temperature. The primary feature of DBD is its ability to generate a non-thermal equilibrium plasma condition in a far easier manner than other methods. This review offers a synopsis of the core ideas, workings, and applications of DBD along with gas discharge plasma reactors and different configurations of DBDs traditional to modern systems based on their versatile applications like ozone production, SD CO_2 lasers, excimer UV lamps, pollution controls, PDP, surface treatment, plasma ignition, agriculture, medicine, photonics, energy sources.

Keywords: Non-Thermal Plasma, Dielectric Barrier Discharge, Micro-Discharge

Introduction

The claim that 99% of matter in the cosmos occupies the plasma state—that exists, being an electrified gas with its atoms split into positive ions and negative electrons—has been made numerous times. Plasma exists as an electrically charged particle(electron or ions) along with a neutral gas that is “quasi-neutral” and possesses a collective behaviour.[1] In physics, the idea of the existence of “plasma” refers to a quasi-neutral ionised gas or a medium which has a specific percentage of particles charged. Plasma becomes a highly conductive gas that reacts quickly to electromagnetic fields as charged species are present.[2] With many significant differences among the properties of the solid, liquid, and gaseous states of matter, plasma is frequently referred to as the “fourth state” of matter.[3] As far as their creation is concerned, it contains basically two types of plasma: Non-equilibrium or low-temperature plasma and equilibrium or thermal plasma. There are certainly several possible ways to supply the energy required for a gas in order to ionise it. A flame is a common example of a thermally heated object while energy has been generated via exothermic chemical processes inside the molecules. When this occurs, the plasma’s constituent ions, electrons, and neutral particles are each in a state of thermodynamic equilibrium or the same temperature; these types of plasmas are simply referred to as thermal plasmas. Thermal plasma, which sustains thermodynamic equilibrium, is composed of gas molecules, ions, and electrons at temperatures of about 20,000 K. In addition, low-temperature plasma is classified as quasi-equilibrium plasma (100–150 ^{O}C) or non-equilibrium plasma (30–50 ^{O}C). A further method for creating plasma for technological purposes involves using an external electric field. The fundamental characteristics of these plasmas, also known as electrical discharges during non-thermal plasma creation, most of the provided energy is focused on electrons rather than heating the entire gas flow. The outcome is that the temperature of gases stays relatively constant. Low-temperature plasma is sometimes known as “cold plasma” or “non-thermal methodology” as a result.[2,4]

A dielectric barrier discharge can also happen in the discharge space if there are many insulating barriers in the current path via metal electrodes. Dielectric-barrier discharges (DBDs), sometimes known as barrier discharges or quiet/ inaudible discharges, have long been linked only to the production of ozone.[5] Siemens’ ground-breaking proposal to employ DBD for ozone formation in 1857 led to the first use of DBD plasma in water treatment. According to what was written in his work, air or atmospheric pressure might produce ozone when a discharge was started inside an annular space located between the two concentric glass ducts. About 1900, this discovery paved the way for the massive industrial manufacturing of ozone in Europe for the purpose of treating drinking water.[6] Finding alternative methods for the decontamination of materials that are heat-sensitive was the goal of the very first bio-decontamination experiments using non-thermal plasmas, which took place at the start of the 1990s. The outcomes were extremely promising, especially when compared to dangerous techniques such as using poisonous gas.[7] The revolutionary application of DBDs in the manufacturing of flat-screen television screens employing AC plasma, revealed in 1996, likewise gained great attraction. Recently, at least two more areas of interest have been added to the list of DBD applications: airflow regulation and medication.[8,9] The former Professor Ulrich Kogelschatz provided a summary of the importance and impact of DBD technology up until the early 2000s, He released his review in 2003, and it is still cited annually, with over 2900 citations in Web of Science. Since then, DBDs have found many uses, with the fields of biology and medicine seeing some of the most fascinating and quick growth[10] and for agricultural applications primarily concerned with altering and enhancing seed germination properties. The cold plasma is produced by utilising the dielectric barrier discharge (DBD) in combination with the fringe field’s ability to induce corona discharge across the tips’ edges to modify the seed interface.[11] Dielectric barrier discharge igniters (BDIs) provide non-equilibrium low-temperature plasma (LTP), a potent ignition accelerator in a large mixture volume, to guarantee engine steady combustion at light and/ or diluted circumstances.[12]

Low-temperature plasmas commonly referred to as gas discharge plasmas, have garnered significant attention in recent decades due to their significance in numerous technological advancements. Over a century ago, the first industrial applications of plasma were in the production of ozone and illumination using plasma sources. Since then, a variety of technological and research fields have made use of plasma processes, including microelectronics, gas lasers, polymer treatments, the synthesis of new materials, safeguarding coatings, etc. These days, air and water purification systems, packaging for food, fruits, meat, vegetables, textiles, and medical equipment are all treated with plasma techniques.[13] Furthermore, new applications for plasma processes have emerged recently. This includes plasma nanotechnology that involves plasma-based production and modification of non-materials, plasma ignition, and plasma aerodynamics. The utilisation of non-equilibrium plasma in the fields of biology and medicine research has become more prevalent recently due to advancements in atmospheric pressure plasma jet production. Some of the applications include dentistry therapy, wound reconstruction, surface purification, cancer cell treatment, and other skin ailments.[13–19] The dielectric barrier discharge (DBD) provides one of the most affordable non-thermal plasma resources between other forms of plasma. It is well known that this kind of discharge is useful for starting chemical and physical reactions in gases. Due to the possibility of its application in an extensive range of disciplines, DBD has been the subject of significant investigation in recent years. Because of its capacity to create extremely reactive plasma at almost room temperature via minimal energy consumption utilising a straightforward reactor system under atmospheric pressure situations, it spans not just material proceeding but additionally applications in the domains of energy and environment.[13,20]

Dielectric Barrier Discharge Plasma Reactors, Properties and Applications

Here we are going through a brief introduction of the generating procedure of plasma and then we aim to produce low-temperature gas discharge plasma reactors that can be used for the making of DBD plasma. Energy is introduced to a neutral gas in order to create plasmas, meaning that accumulate charge carriers.[21] When photons or electrons with enough energy interact along with the gas’s neutral substance or atoms, they can establish ions and electrons inside the gas phase (this phenomenon is known as photo-ionization or electron-impact ionization, respectively). Stable-state plasma finally forms as a result of an accumulation of charged particles that are ultimately balanced by charge carrier losses. Fortunately, there are several ways to create plasma, including adding an external electric field (electric discharge), heating a neutral gas, or exposing plasma via a significant electromagnetic field.[22] Figure 1 demonstrates the various techniques for the generation of plasma. Low-temperature plasma has gained increasing interest in recent years because of its special benefits, which include its straightforward construction and inexpensive operation. In general, low-temperature plasma can be produced using a variety of techniques, including radio frequency discharge, microwave discharge, corona discharge, dielectric barrier discharge, direct current glow discharge (DC-GD), and gliding arc discharge. Dielectric barrier discharge (DBD), one of these discharge techniques, produces plasma on a large scale that is better suited for plasma chemistry and surface treatment. Here we try to summarize different kinds of gas plasma reactors, properties of DBDs, and respective applications that will be discussed in detail ahead.

This study aims to provide an overview of various DBD configurations and their respective uses. In the previous section, we saw the electrically generated gas discharge plasma. This type of plasma is low-temperature plasma. To confine the gas discharge plasma is easy in comparison to thermal plasma, and gas discharge plasma is operable in low temperatures or pressure. For this reason, DBD plasma has a versatile application and has future advancement possibilities. Also, there are a lot of difficulties in generating plasma in definite shape or size, desirable densities of ions or electrons, and interacting behaviour of plasma; many other problems are seen. So, most of the plasma is generated based on their numerous properties and applications. In Figure 2 we demonstrate those for better understanding for readers. Figure 2 column 1 shows some low temperature and atmospheric pressure plasma rectors based on generating processer of electrical discharge. Column 2 describes the properties of discharge plasma or DBDs and column 3 includes a versatile application of DBD plasmas.

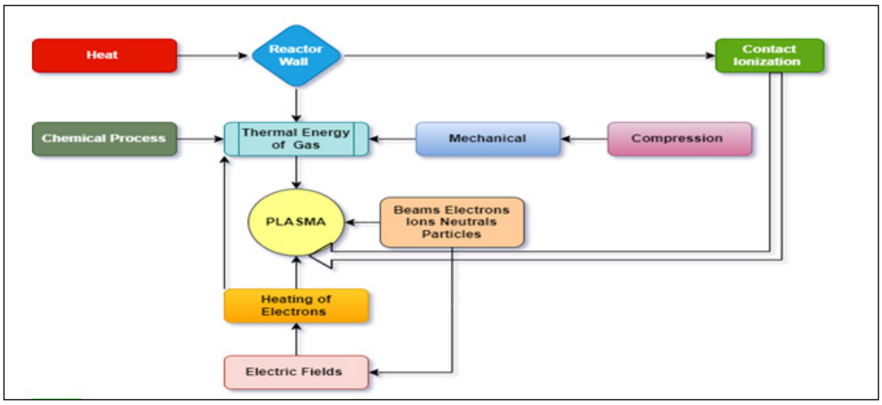

Figure 1.Different Methods for Producing Plasma like Electrical, Chemical, Thermal Heating, etc.

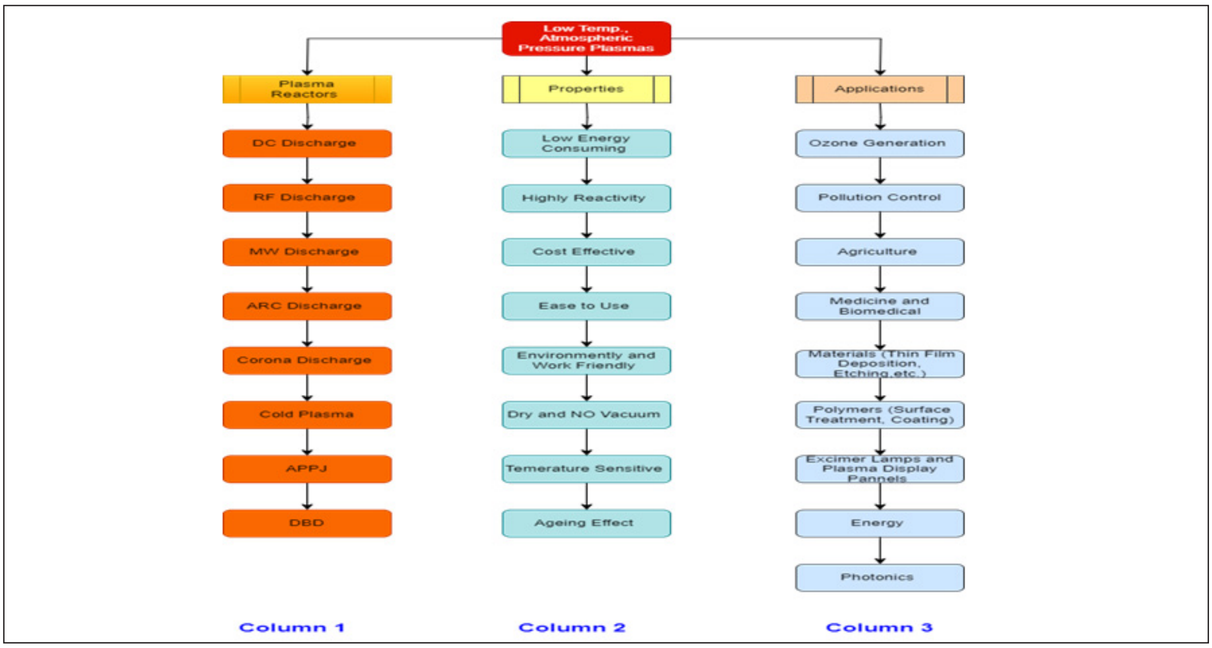

Figure 2.Column 1: Configuration of Different Gas Discharge Plasma Reactors, Column 2: Properties of Gas Discharge Plasmas, and Column 3: Application of DBD Plasmas

RF Discharge-Radio Frequency Discharge, MW Discharge-Microwave Discharge, ARC Discharge- An electric arc discharge, APPJ- Atmospheric pressure plasma jets, DBD-Dielectric Barrier Discharge

Physics of Dielectric Barrier Discharge Plasmas

DBD plasma is the gas discharge of non-thermal plasma or low-temperature plasma which works at low pressure like atmospheric pressure means in DBD the electron temperature is much greater than the ion temperature and the neutral particles temperature, so the mobility of the electron is very high. Due to this feature, it is highly reactive and makes reactive species with interacting substances (solid, liquid and gaseous forms). In a variety of fields, DBD plasma is a non-destructive approach. Two primary methods in the study of gaseous discharge may be utilised to prevent a discharge's corona from sparking. Using a power source with nanosecond pulses is one method.[23] A dielectric barrier inserted into the discharge gap is the alternative strategy. For the purpose of avoiding the occurrence of full breakdown, dielectric material has been introduced into the discharge gap to restrict the discharge current. High-frequency AC voltage, pulsed-DC voltage, microwave, or radiofrequency power supply are frequently used to power DBD plasma devices. Barrier discharges, often referred to as quiet/ silent discharges or dielectric-barrier discharges, offer a straightforward method for creating non-equilibrium plasma conditions in gases under atmospheric pressure. With a dielectric barrier separating the two electrodes, an audible discharge (DBD) is produced. The space filled by gas is tiny—usually a few millimeters. To maintain these discharges, a voltage of 1–100 kV and frequency of 50 Hz–1 MHz are required. A vast number of filaments with a diameter of approximately 0.1 mm are formed because of the streamer breakdown mechanism. The dielectric materials between the electrodes restrict the current. The dielectric's surface is occupied by the charge carriers that flow from the plasma to it, counteracting the external electric field. As a result, the filaments have an extremely brief lifespan (1–10 ns). The filaments have a current density of 100–1000 A cm^{-2}, an electron density of 10^{14}–10^{15} cm^{-3}, and an average electron energy of 1–10 eV.[5,24] Using a dielectric material wrapped around two flat metal electrodes; this method prevents sparks from occurring by blocking electric currents. Any neutral or inert gas mixture flows between two electrodes in a closed target chamber where it is ionized to form plasma products. One electrode is linked to a high-voltage circuit, and the other electrode is connected to the ground. It is a non-equilibrium discharge of direct current or alternating current that usually operates between 0.05 and 500 kHz with a wide range of gas pressures (usually between 10^4 and 10^6 Pa), and Its energy needs for operation vary from 10 to 100W.[25,26] The dielectric barrier discharge efficiency is dependent on several factors, such as the gas utilized, the operating voltage, and the spacing between the electrodes. The potential and the intensity of the electric field across the electrodes at the distance where the DBD plasma forms are largely determined by the electrode geometry. Both the depth of the dielectric barrier as well as the interelectrode spacing are crucial factors in the creation of DBD plasma. We have described here different types of electrode configurations for generating DBD plasma.

Parallel-Plate Electrode System

The gas gap in a plane-parallel dielectric barrier discharge (DBD) setup is uniformly spaced. For the duration of the discharging phase, the burning voltage, or plasma ignition voltage across the gap, remains relatively constant.[27] Two symmetric electrodes are where the discharge is produced see Figure 3 (a). The brass electrodes have a smooth surface. Their diameter is 50 mm, and their thickness is 10 mm. With a 0.5 mm dimension, the top electrode may be moved while the bottom electrode remains fixed. A 2 mm diameter glass plate serves as the dielectric barrier. With using a high-voltage AC power source, a voltage of 1–2 kV is provided at an oscillation frequency of 30 kHz. Argon flows at a rate of flowing of one litre per minute, and the distance between the electrodes may be adjusted from 0.5 to 2 mm. The trials are conducted with 0.5 and 1–2 mm gap separation. Measurements using optics and electricity were used to examine this system. The power balance method and the line intensity ratio method were used to measure the electron temperature and density in the discharge. By measuring contact angles, the impact of this plasma procedure on the surface characteristics of polymers was also examined. Contact angle measurements on samples treated with and without plasma demonstrated that this discharge significantly increases the polymer surface's wettability.[28] This configuration of DBD is used in various applications by the varying applied voltage, dimensions of the electrode, discharge gap, thickness of dielectric material, and insert gas. Applications are like carbon dioxide decomposition, alternating current (AC) is used in an AC parallel-plate plasma reactor (AC-PPP) that operates at atmospheric pressure to remediate CO_2. This reactor can run at atmospheric pressure and has an extremely simplistic, inexpensive design that makes scaling it up for commercial use relatively easy. The new design is based on a high voltage (HV) discharge with extra intake and output metal pipes between two parallel electrodes. This increases the treatment area and, as a result, the conversion efficiency by extending the electromagnetic field inside these pipes.[29]

Cylindrical Electrode System

Devices with flat or cylindrical geometries can be configured as dielectric barrier discharges (DBDs). Applying a high voltage between two electrodes—at least one of which is coated in a dielectric barrier material—creates DBDs. The Arc discharge is stopped by the dielectric. The conventional cylindrical electrodes DBD system concept shows two electrodes mounted horizontally parallel to one another in a stand. The system's electrodes are made to make it simple to pass lengthy rolls of fabric and other materials for ongoing plasma therapy. By measuring the contact angle, it was possible to determine if the cotton fabric improved in wettability after passing through the discharge between the electrodes. After 20 treatment cycles via the discharge, the cotton sample, which was hydrophobic before to treatment, became hydrophilic.[28] Based on the planer DBD plasma reactor, many electrode configurations are available, such as wire-plate, mesh-plate, and single (multi) needle(s)-plate. These layouts were shown to lower the first breakdown voltage when compared to the conventional plate-plate electrode arrangement, suggesting that they could find use in industrial applications. Such designs of plasma reactors were also used for pollution management and plasma-based processes, and satisfactory performance was attained.[30]

Coaxial Electrode System

A high-voltage AC power source applies a radial electric field, and it is intended to create an annular gap between two coaxial tubes see configuration in Figure 3(b). The moving gas in the annular gap has an electrical breakdown as a result. The primary applications of DBD using a coaxial cylindrical electrode system are chemical synthesis (ozone production) and engine exhaust gas purification.DBD plasma enhances combustion primarily through three pathways: thermal, kinetic, and transport. This is because it may create heat, electrons, excited molecules, long-life intermediate species, radicals, ions, ionic wind, and Lorentz force. PACAs (Plasma Assisted Combustor Actuators) were utilized to introduce gaseous fuel and ionized airflows into the combustor to improve combustion performance. In a coaxial DBD-PACA, the lowered electric field is less the closer the inner electrode is to the ground. The lowered electric field increases with proximity to the high-voltage outer electrode.[31] Recently, there has been an investigation into the possible use of non-thermal atmospheric pressure plasmas in agricultural applications as a promising substitute that might boost food production while having negligible effects on the environment. For seed modification, the DBD generates two distinct chemically active states of the system when it operates with argon and helium. While a physiological temperature was ensured by regulating the exposure period, the temperature modification was tracked to ensure the safe handling of seeds. Wettability increased noticeably and germination accelerated with both treatments. Different-sized and shaped plant seeds can be treated using coaxial DBD reactors. Additionally, they are easily scalable for use in agriculture and the treatment of big batches of seeds. Using the stated argon discharge (with air impurities), the current study demonstrated a decreased water contact angle (WCA) (82% reduction) and quicker germination acceleration (60% faster after 24 h) for winter wheat seedlings.[32]

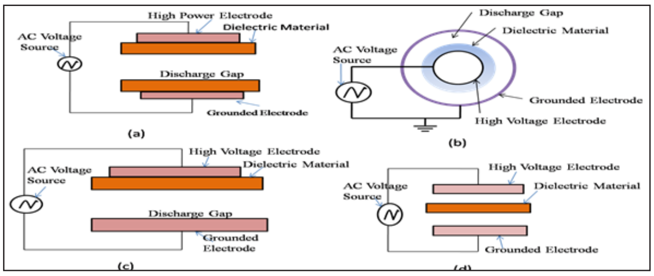

Figure 3.Different Configurations of DBDs, (a) Parallel Plate DBD, (b) Coaxial DBD, (c) Surface DBD, (d) Volume DBD

Volume Dielectric Barrier Discharge Plasma

Two metal electrodes facing one another and shielded from one another by a dielectric barrier make up typical DBD plasma. It is possible to introduce the working gas into the gap between the electrodes. The strong electric field in this area will then allow for the generation of plasma. This type of arrangement is categorized as plasma with surface-DBD (SDBD) or volume-DBD (VDBD) as shown in Figure 3(c) & 3(d). The sample is positioned in the discharge zone of surface-DBD devices. The dielectric barrier for this device is positioned in between the two electrodes. In this instance, the two areas between the electrodes and the dielectric materials each produce plasma independently. By using ambient air as the working gas and operating at atmospheric pressure, VDBD reduces all costs associated with plasma pre-treatment. This technique works well for thin-film treatments in which the sample may be positioned in the area of plasma.[33] By employing the same concept, dielectric materials inside a cylinder may be used to create VDBD. We refer to this type of arrangement as cylindrical DBD plasma. Among the electrodes both within and outside the cylinder, plasma can be produced inside the cylinder. The primary benefit of cylindrical DBD plasma is that, as opposed to direct plasma treatment, gas-phase products are used at the devices' exit. For gas phase catalysis, cylindrical VDBD plasma devices are widely utilised.[34] Recent studies show that volume DBD is used in aircraft icing. To reduce the ice on aero-planes, dielectric barrier discharge (DBD) plasma actuators can be employed. While using the same amount of power, DBD plasma actuators may suppress ice accretion more effectively than traditional electrical film heaters.[35,36]

Surface Dielectric Barrier Discharge Plasma

When dielectric material covers one or both electrodes, a surface discharge is referred to as a dielectric barrier discharge (DBD). An SDBD plate's surface is the place where the plasma is produced. A pre-ionization DBD may be utilized to quickly ignite VDBD and provide an evenly dispersed discharge in the gap. It is possible to construct a specific small and cost-effective DBD plasma generator using the piezoelectric direct discharge technique. A cold plasma discharge known as the Surface Dielectric Barrier Discharge (SDBD) happens at atmospheric pressure. Surface DBD (SDBD), an alternative to VDBD, was created to get over its dimension's limitations. Because SDBD devices can produce ionic wind, which is very helpful for space flight, they were originally primarily designed as actuators. The dielectric barrier may contain one or both electrodes in SDBD plasma. A huge surface discharge area may be achieved in SDBD plasma construction. These DBD plasma electrodes can be arranged in a co-planar shape. By minimizing the space between the two electrodes, this shape lowers the applied voltage needed to generate plasma.[13,37] SBDs are often utilized in aerodynamics; through the application of an electrohydrodynamic (EHD) force, SDBD plasma can generate an ionic or electric wind. While charged particles become mobilized via the electric field and impart momentum to neutral air particles, a force is formed, ozone production, material surface treatment, and other applications.[38] Another application for SDBD plasma is as a plasma source for gas conversion. The gas flow must be effectively mixed with the plasma to create the plasma filaments. The SDBD actuator mechanism can provide a plasma force toward the fluid, causing vortices to form over the electrodes. The species transformation and plasma gas combination can be improved by the vortices.[39] In the actual uses of this technology, the discovery of Dielectric barrier discharge (DBD) plasma with flexible structures marks a possible paradigm change. When compared to the well-researched rigid-structure DBD. FXDBD plasma's flexible structure creates new opportunities that traditional rigid-body plasma systems are unable to adequately address, especially when it comes to addressing biological targets' intricate surface features. The application of flexible dielectric barrier discharge (FXDBD) plasma devices for treating bigger surfaces, non-flat surfaces, or curved items has drawn a lot of interest. Flexible electronics technology is developing quickly, allowing potentially limitless design and manufacturing flexibility for FXDBD devices. Now we discuss the new or flexible DBD configurations.[40]

Flexible Dielectric Barrier Discharge Plasma

The majority of DBDs that have been documented employ inflexible dielectric barriers like quartz and glass. These substances also serve as building blocks for creating electrodes. Most of the specimens that have been handled have bents and curves (Figure 4 shows a few examples of FXDBD). Because of these characteristics, it is more difficult to achieve homogeneous treatment using the inflexible designs of traditional DBD. The creation of bendable and curved FXDBD plasma structures offers a potential remedy for this problem. The FXDBD plasma device may be readily produced in concept thanks to flexible electronics technology, which involves fabricating the conducting electrodes using an insulating substrate that is not stiff. FXDBD's flexibility allows it to be bent, twisted, or coiled over curved or uneven surfaces, improving treatment consistency across the treated region.[41] Substrates dielectric materials and electrode materials are the two categories into which the materials for flexible DBD plasma are currently divided. A thin film of dielectric material is necessary for adequate insulation, avoiding leakage current, and controlling the charges transferred from one electrode surface to another during the discharge procedure for plasma devices that need high voltages to function. Generally non-printable, inorganic materials such as silica, alumina, and other high permittivity oxides are used in electronics on flexible substrates. Materials constructed from polymers show promise in applications where high levels of flexibility, transparency, and emissive qualities are needed. Polymer materials are lightweight, diverse, inexpensive, and very flexible. Due to their superior flexibility and strong resistance, polyimide film (PI) and polyethylene terephthalate (PET) are now the most popular polymer materials employed as dielectric materials in FXDBD devices. Paper, in addition to polymer materials, has unique qualities including being inexpensive, lightweight, and environmentally benign that make it a promising material for flexible electronics.[42]

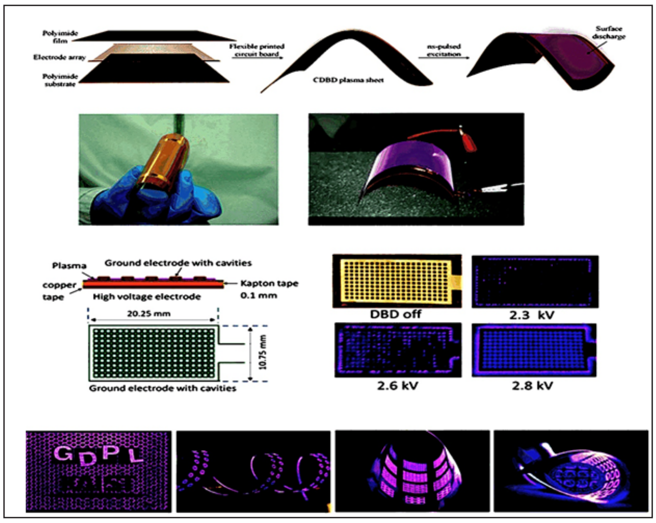

Figure 4.A Few Examples of FXDBD40

Fundamental Characteristics of DBD

Across the gap between the electrodes, DBD plasma usually shows an even flow of plasma. It produces species that are reactive, like ions, radicals, and excited molecules, and these can cause chemical reactions in the environment around it or on adjacent surfaces. Air, nitrogen, helium, argon, and other gases can all be used to create DBD plasma. The characteristics and reactivity of the plasma can be modified depending on the needs of a certain application by selecting a different gas. DBD plasma equipment are adaptable instruments for both commercial and research applications because they can be expanded and developed for a wide range of uses, spanning small laboratory installations to huge industrial systems. There are many important properties of DBD, a few of which are discussed ahead.

Non-Thermal Equilibrium Nature

Since electrons transmit energy rapidly when they collide with surrounding electrons but only weakly when they collide with atoms or ions due to the huge percentage of atom or ion mass to the electron mass, it is conceivable to keep in mind a distinct electron temperature in non-thermal plasma. The strongest manifestation of this phenomenon occurs in plasmas devoid of internal degrees of freedom in molecules.[43] So for the non-thermal equilibrium plasma temperature of the electron is higher in comparison to the ion or atom ($T_e > T_i/T_a$) and they exhibit a local thermodynamic equilibrium, which makes it highly reactive.[44] The primary attribute that has greatly contributed to DBD's utility in material processing is its non-thermal equilibrium nature. Establishing non-thermal equilibrium plasma conditions in DBDs is a far simpler process than in other techniques like electron beam injection, high-pressure discharges with rapid pulses, or low-pressure discharges. These discharges are appropriate for material processing and bio-film coating since they do not reach thermal equilibrium.[45,46] Non-thermal plasmas require less power and can be produced at lower pressures. In gases with lower pressure, electric discharges can produce this kind of plasma.[47]

Micro-Discharge

Numerous current filaments, referred to as micro-discharges, are produced in DBD because of the ambient gas breaking down. These micro-discharges are dispersed irregularly in time as well as space. The amount of voltage that is delivered by the electrodes determines how many micro-discharges occur. The polarity involving the dielectric determines the form of the micro-discharge foot on it. The pressure-distance product (Pd) often determines the parameters of gas discharge. To generate steady glow discharges, one must fall within a specific Pd product range. According to Foest et al., if the plasma is physically limited to chambers with dimensions less than 1 mm, referred to as micro-plasmas, steady glow discharge plasmas at increased pressures are able to be produced and sustained with simplicity.[48–50] The charge that is collected on the dielectric or moved within the micro-discharge has a significant impact on the DBD's properties because it not only modifies the electric field in the gas separation but also intensifies the atomic processes within the discharge. The charge needs to play a significant role in those cutting-edge apps' optimal efficiency and associated features. O_3 generation and excimer excitation are proportionate to the transmitted charge in the volume discharge (VD), much like in ozone generators and radiation sources.[51] Consequently, over the last few years, there has been an increased interest in the field of micro-plasmas driven by their ability to produce stable glow discharges, thereby triggering an increasing number of potential applications. Generally, micro-plasmas have the prospect of being used in various medical and industrial applications including sterilisation, medical treatment of human skin, surface activation, nano-material synthesis, and thin film coating. To date, micro-plasmas have been developed for local medical treatment of skin diseases, and especially for the treatment of corneal infections. Additionally, by evaporating solid electrodes, several metal or metal-oxide nanostructures of various compositions and morphologies are constructed. Finally, micro-plasmas were found to reduce aqueous metal salts and to produce colloidal dispersions of nanoparticles when mixed with liquids.[26,52–54]

Applications of DBD Plasma

Gas discharge plasmas are utilised in a variety of applications such as light sources, plasma display panels, lasers, etching of surfaces, and deposition of thin layers in the semiconductor industry. In addition, uses are found in surface modification, deposition of protective coating, analytical chemistry (for the analysis of mainly solid materials), and biotechnological and environmental applications.[5,26,55] Some of them we discuss here.

Ozone Generation

Ozone, often known as O_3, is an oxygen allotrope that is tri-atomic in nature and has a strong smell. Ozone begins to condense around -112 °C, producing a dark blue liquid with explosive qualities.[56] Ozone has an oxidation potential of 2.07 V and breaks down spontaneously and quickly into oxygen in both air and water. Its quick breakdown and strong oxidative strength make it useful against a wide range of microorganisms.[57] Ozone's effectiveness in both air and water is among its primary features, which makes its usage possible as an antibacterial agent. Ozone, being one of the most potent oxidants, finds extensive use in agriculture, textiles, water treatment, food processing, and storage, among other industries.[58] Dielectric barrier discharge (DBD), one of the various techniques, has shown to be one of the most successful in producing ozone and is widely applied at both commercial and industrial sizes.[59,60] Ozone is established via the dielectric barrier discharge plasma (DBDP) reactor, which makes use of the plasma glow that develops between the active electrode and the dielectric barrier. Once the air crosses the gap, airborne particles or oxygen molecules will collide with electrons in the air, causing them to ionize and dissociate. Stress, electrode material, reactor geometry, reactor setup, pressure, gas flow rate, frequency, humidity, power source, temperature, and reactor gas supply are all known to have an impact on ozone manufacturing.[59,61] An extensive history of using ozone has been seen in the treatment of water, particularly in Europe. It was discovered around a century ago that ozone's germicidal and veridical properties may supply clean drinking water to regions that had previously been at risk from cholera and typhus outbreaks. Disinfection, the reduction of tri-halo-methane, a disinfection byproduct, colour, taste, smells, pesticides, and the elimination of iron and/ or manganese are the primary goals of ozone treatment for water. The paper sector is the second most significant and rapidly expanding large-scale user of ozone. Without the use of chlorine, pulp can be treated in a closed circuit by mixing bleaches that contain oxygen, ozone, and hydrogen peroxide.[5,58,62] The majority of technical ozone generators employ 1–2 m long and 20–50 mm diameter cylindrical discharge tubes. Within the stainless-steel tubes, glass tubes are installed to provide a small annular discharge area. The conductive coating, such as a thin layer of aluminum, forms the high-voltage electrode inside the glass tubes. Borosilicate glass is the chosen dielectric material (Pyrex, Duran). Layered enamel coatings with optimized dielectric properties are also used for steel tubes in sophisticated ozone generators. Huge ozone generators may create up to 100 kg of ozone an hour using several hundred tubes.[5,59,63] The amount of energy used and the concentration of ozone is dependent on a number of factors, including the DBD reactor's structure (axial, coaxial, or cylindrical) and the gases it fills (nitrogen, argon, or a combination of gases).[64]

Plasma Display Panels (PDP)

The alternating current plasma display panel (AC-PDP), a typical dielectric barrier discharge (DBD) technology, offers several good features, including a big screen, a thin and light flat panel, a broad viewing angle, rapid response, high resolution, and complete digitisation, etc.[65,66] In the current consumer electronics industry, it is one of the most favoured wall-hanging flat-panel TVs and high-definition TVs. The recurrent effect of wall-charge buildup on the external surface of the dielectric layer in discharge cells underlies the functioning of AC-PDP. The memory effect produces an AC-PDP voltage functioning tolerance by efficiently reducing the maintained voltage. It is essential to reducing the consumption of energy and achieving stable AC-PDP functioning. The wall-charge build-up has up till now been considered a beneficial aspect of AC-PDP functioning.[67,68] Picture sticking is the result of an itinerant strong sustained discharge that lasts for many minutes throughout a sustained period. When a previous picture is constantly presented for a few minutes, a ghost image persists in the succeeding image. The phosphor layer's degradation was the primary cause of the ghost image's reduced brightness; the brilliant image's luminance is mostly generated by the high discharge that happens during the sustain period (Testing in MgO surface or phosphor layer for 42-in plasma display panel).[69] The discharge qualities of the dielectric layer are significantly influenced by its surface characteristics, including its shape and orientation. Various surface conditions can yield distinct gas DBD characteristics.[70,71]

PDPs have a decreased discharge gap width of 80–100 pm and a breadth of around 200 pm for each cell. In order to minimize intercellular communication, ribs that are usually 50 pm thick and 100 pm high are placed between adjacent cells. These cells may be created using somewhat cheap production procedures such as thick film printing or by sandblasting or engraving onto a flat glass plate. At filling pressures between 10 and 100 kPa, a combination of helium and xenon or neon and xenon serve as the filling gas. Every single cell may be addressed with two sets of thin electrode strips arranged perpendicularly. The electrodes of ac PDPs are covered with magnesium oxide thin protective coatings and dielectrics. The main source of the electron beam is the photoelectron emission from the cathode, which is caused by radiation from the working-gas atoms excited by fast heavy particles in an extremely non-uniform electric field within the cathode cavity. MgO's low sputtering rate ensures long lifetimes, and its high coefficient of secondary electron emission is accustomed to lower the operating voltage. Ions and rapid atoms are likewise dispersed by such a field, which lowers their fluxes towards the cathode. The observed results suggest that open-discharge microstructures with a cathode cavity can serve as a foundation for the creation of extremely efficient light sources and plasma panels. These microstructures make it possible to convert electric energy into light very effectively. 200 V integrated driver circuits can power PDPs.[5,72] The dielectric barrier discharge in mixes of Ne–Xe or Ne–Xe–Ar was determined for an AC-PDP model. The above models were subsequently employed to assess the gas composition-pressure relationships of electron temperature, plasma density, excited atom density, wall charge density, discharge current density, excimer density, and VUV intensity in order to analyze the processes of VUV radiation and discharge productivity along with the luminous efficiency.[73,74]

Plasma in Agriculture

The previous two or three decades have seen an abrupt population rise, which has raised demand for food that is healthy as well as allowed agriculture to grow. With the change in consumer demands and food safety guidelines, food processing technologies have changed as well as the load on the environment and natural resources will consequently increase dramatically.[75] Thermal food processing is still one of the key methods utilised in the food processing industry, having been around for more than

200 years.[76] High heat treatment can have unfavourable impacts on food, such as colour, texture, and nutritional loss, which encourages researchers to look into additional possibilities for non-thermal handling of food.[77] Infrared heating, ultrasound, ohmic heating, pulsed electric field, high-pressure processing, ozone processing, pulsed light, cold plasma, and dielectric heating (microwave heating and radiofrequency) are some of the new processing techniques that researchers are working on developing that preserve the majority of their desirable features. These newly developed methods provide little processing, preserving food's sensory qualities while protecting its bioactive components and prolonging its shelf life. New methods have several uses in the food industry, including lowering heating and residence times, enhancing food quality, increasing energy production, managing mail-lard and other chemical reactions, and protecting the environment from stress.[4] A novel technique for decontaminating fresh produce is the use of cold plasma. When used in a variety of food products, such as grain, meat, poultry, dairy, fruits, and vegetables, as well as packaging, plasma processing is a versatile technique. Regarding the attainment of an environmentally friendly green economy in the agricultural sector, many paths are being investigated as substitutes.

Specifically, direct seed surface treatment using Dielectric Barrier Discharge (DBD) technology has become a topic of increasing attention in the agricultural field. Several research works have demonstrated the advantages of using non-thermal processing techniques (NTPs) to control biological materials related to seed contamination, surface feature modification, enzyme activity, and metabolomic processes, all of which enhance the formation of seeds and initial establishment. This ecologically friendly technique has gained a lot of attention as a way to support sustainable agriculture since it offers a competitive alternative to conventional farming techniques.[75,78] Low atmospheric pressure or cold plasma produces highly energetic electrons, ions, UV radiation, reactive oxygen, and nitrogen species (RONS) in atmospheric air, and these materials have a variety of uses in groundwater treatment and agriculture. In addition, DBD plasma enhanced the conductivity of electrical current and oxygen dissolution while decreasing various levels of physical measurements including pH, turbidity, total suspended particles, and all the dissolved solids. Along with the decrease in the content of heavy metals like iron, cadmium, lead, and zinc, there was also a notable decline in the number of certain types of chemical parameters are as calcium, phosphorus, sodium, manganese, and chromium. On the other hand, nitrite, nitrate, and sulphur proportions increased progressively. In addition to acting as an antibacterial, soaking seeds in plasma-activated water (PAW) promotes plant development and seed germination.

Because plasma therapy interacts complexly with organic components and live cells, it can have a wide range of impacts on seed shape. It was discovered that plasma chemistry can regulate the germination of a number of distinct crop species. More specifically, without appreciably changing the proportion of germination, implantation may be either sped up by improving the wettability characteristics of the seed's exterior or postponed by applying a strong plasma-reactive layer. For pea, radish, maize, and bean seeds, germination was postponed using selected gas and plasma circumstances; for soybean and corn seeds, germination was expedited. The modification of the surface characteristics and the decrease in pathogen/ chemical contamination of plant seeds are additional effects of plasma therapy.[79,80] Direct plasma discharge in exposure to seeds may, under the influence of some experimental scenarios, have detrimental effects on the seed cells, including membrane damage, cell death, and protein breakdown.[81] Comparing the stiffly structured DBD plasma to the flexible FXDBD plasma, more applications become possible. FXDBD plasma, for example, works wonders when it comes to sterilizing curved surfaces or items since it stops the growth of germs in the treated region. Applications in food technology, where samples come in a variety of sizes and forms, can further develop this benefit. Fruit and meat items can have their surfaces uniformly treated by bending or curving FXDBD plasma. FXDBD plasma affects how wounds are treated, particularly in curved or large-area settings.

Both thermal and non-thermal plasma are employed in the food and agriculture industries for the following:[82]

- Purification of water and wastewater,
- Making use of and managing industrial waste pest management and soil treatment,
- Removing odours from the air during the production of agriculture and using waste,
- O_3, a deodorising and antibacterial chemical, is used in typical freezers for food pasteurization, disinfection, and preservation.
- Sterilization and conditioning of biomaterials, including food, as well as food packaging and storage, improvement of fruit development, plant growth, and seed germination.

Surface Coating and Modification

Adhesion, painting, or printing on many plastic surfaces can be challenging or even impossible due to their resistance to moisture. Activating such surfaces by plasma treatment—also known as "corona treatment"—is feasible in many situations. A dielectric-barrier discharge is employed in most applications. A dielectric barrier is usually provided by the workpiece, a coating on the transport wheels, or high-voltage electrodes. Large foils are treated on either side or both sides by passing them through a silent discharge at a highly intense rate that is kept constant by applying a constantly fluctuating high-voltage circuit across a drum coated in a dielectric and an electrode with a cutting edge. Electrode assemblies with several parallel knife edges are employed in numerous applications. A speed of around 10 m/s is used to process foils up to 10 m in width. About 100 kW of discharge power is needed for this. Operating frequencies between 10 and 50 kHz are useful. Additionally, research has been done on thin-film development with dielectric-barrier discharges.[83]

A significant rise in surface free energy is the result of an air-pressure dielectric barrier discharge, which is comparable to low-pressure discharges. After being treated by atmospheric pressure DBD (APDBD), it is stated that the surface free energy of untreated polymers increases from 20–30 to 50–70 mJ/m^2 increasing the material's surface wetness.[84] As a result, APDBD improves the material surface's adherence, printability, and dye absorption. Enhancing wool and fabrics as well as plasma treating insulated cables and wires are examples of recent experiments. Radicals created in the plasma while in surface activation break chemical bonds of the surface layer, leading to the emergence of new species with distinct characteristics. As a result, this near-surface area is altered without affecting the material's desired bulk qualities.[85] The most reactive elements in gas plasmas are found to be oxygen atoms, which causes the exterior layer to accumulate oxygenated carbon nuclei.[13] In this regard, many non-equilibrium "cold" plasma discharge methods have been devised that give the necessary surface characteristics for the polymers in question by altering their surface. Dielectric barrier discharges are among these different types of plasma approaches, and they are clearly extremely useful for the stimulation or an alteration belonging to polymer surfaces because they allow for the potential for essential surface chemical transformations to be induced with material under or close to atmospheric pressure, without the massive engineering expenses usually connected alongside vacuum-based plasmas.[86] Surface wetness and surface chemistry of polytetrafluoroethylene (PTFE), polyimide (PI), and poly (lactic acid) (PLA) films are modified by dielectric barrier discharge (DBD) plasma treatment to the surfaces.[15]

Plasma in the Medical Field

Since non-equilibrium plasma may produce high concentrations of reactive elements while keeping the gas's ambient temperature close to room temperature, it can safely come into touch with biological tissues without burning them. Because of this unique characteristic, a brand-new field known as plasma medicine was created.[87] Medical devices, through biomaterials, primarily communicate with the biological surroundings at their surface. Furthermore, the intrinsic or directed surface properties of such biomaterials—such as their chemical composition, cleanliness, texture, surface energy, corrosion/ erosion resistance, etc—as well as the subsequent effects these characteristics have on biological organisms, determine how biological tissues react to them. Medical implants' surface characteristics can be intentionally modified to improve their functioning and biocompatibility using a variety of techniques, including mixing, chemical treatment, ion irradiation, grafting of functional groups, thin film implantation, and plasma therapy.[88] Numerous subjects are the subject of continuing research, including detoxification, dentistry, cosmetology, blood coagulation, cancer therapy, and wound healing.[89–95] The adaptability of plasmas and their ability to produce huge volumes of reactive species in conjunction with electric fields, photons (IR, visible, and UV), and charged particles have led to their triumphs thus far.[96–98] The temperature properties of plasma played a major factor in some of the earliest uses of plasma for medicine. Medical professionals have traditionally used heat and high temperatures to remove tissue, sterilise equipment, and cauterise wounds. The focus of research on plasma utilisation in medicine has recently switched to the exploitation of non-thermal effects.[65] In low thermal loading environments, non-thermal air pressure plasma generators provide an effective way to produce chemically active radicals. These devices' capacity to function apart from vacuum chambers lowers installation and operating expenses overall while permitting the processing of mechanically delicate materials including human tissues as well as biomaterials.[91]

Non-equilibrium plasmas have been demonstrated to be safe, effective, and non-harmful to tissue when it comes to inactivating different parasites and alien species. A variety of atmospheric pressure plasma generators, such as plasma needles, floating electrode DBDs, micro-hollow cathode discharge air plasma jets, and other different types of plasma jets, have been generated for a broad range of biomedical and industrial applications.[23,91,99] It has been shown that atmospheric pressure plasma jets are appropriate generators of low-temperature, non-equilibrium atmospheric pressure plasmas. Instead of merely producing plasma plumes in small discharge gaps, the plasma jet devices also produce plasma plumes in wide space. As a result, the size of the objects to be treated is not restricted when using them for direct treatment.[99] Before being decontaminated or sterilised, the equipment in medical therapy must be well cleaned, and plasma sterilisation is needed to be a part of an extensive treatment process that also involves cleaning processes.[2] Agricultural and biological operations can benefit from the antimicrobial agents produced in plasma, including charged and excited molecules, reactive oxygen species (ROS), atomic oxygen (O), reactive forms of nitrogen (RNS), atomic nitrogen (N), nitric oxide (NO), and, in the event of electrical discharges with water admixtures, hydroxyl ions (OH) and hydrogen peroxide (H_2O_2). Physical and chemical phenomena that affect biological items include etching processes, heat, alternating electric fields, high-energy UV radiation, and their significance in the processes of decontamination, sterilization, surface modification, and medical treatment. The wide variety of plasma reactor types available for use in plasma medicine, being capable of adjusting reactor factors to guarantee the antimicrobial activity of plasma particles, and the ease of access to small, enclosed spaces are some of the factors contributing to plasma's high efficacy in decontamination, sterilization, and healing.[82] The following general three categories may be used to organize these applications as given in Table 1:

- Preparing biocompatible surfaces using plasma assistance
- Using atmospheric pressure plasma directly for medicinal purposes in vivo
- Medical environments: plasma decontamination and sterilization

Table 1.Various Applications of Plasmas in the Medical Field

Types of Plasma Reactors	Applied Fields
Cold plasma applications	Pathogen, bacterial, fungal, and virus inactivations
Cold plasma treatment	Food contamination by fungi, wound healing, dental care, tumours, stem cells, and progenitor cells
Non-thermal plasma (atmospheric pressure plasma jet, DBD)	Sterilization of blood, surface wounds, and tissues from humans and animals helping with skin cancer treatment, Therapy for cavities in dentistry, applying biocompatible film coatings to dentures, contact lenses, and implants, The creation of bioactive substances and medications using live tissue engineering biological molecules are immobilized, cell surfaces are altered to regulate behavior, and blood adhesion is enhanced, Sterilization of surgical and medical tools, particularly those composed of materials and textiles that are not heat-resistant, manufacturing polymer-based biosensors and thin, amorphous films for biochemical and medical analysis are examples of medical diagnostics.

DBD Plasma in Ignition

Over the past 40 years, plasma discharges have become known as a source for improving combustion via the examination of the relationship between electrical energy and combustion, which dates back more than a century. Prior research enhanced combustion using an electric field. Heat engines employ ignition devices to start combustion by lighting the fuel-air combination. A sharp rise in electrons and ions influences the reaction pathways and quickens the pace of chemical energy conversion when plasma energy is linked to the flame's reaction zone. Since the invention of internal combustion (IC) engines and spark ignition systems more than a century ago, thermal equilibrium plasma has been used to govern combustion. The drawback of equilibrium plasmas, such as thermal arcs, sparks, etc., is that heat is deposited as the primary means of transferring energy in a reactive mixture. To achieve great efficiency in a variety of applications, the same concepts are still utilized today. The prospect of plasma-assisted techniques for ignition and flame stabilization has recently triggered a boost in interest in the possible use of non-equilibrium plasma for combustion regulation and ignition. Non-equilibrium plasmas may effectively direct energy transfer to certain flame degrees of freedom, which might quicken branching processes and ultimately raise flame speeds. The ignition procedure for internal combustion engines is expected to be enhanced by a quasi-non-equilibrium system that combines the advantages of non-equilibrium kinetic effects with ohmic heating.[100,101]

When employing a discharge to start combustion or maintain a flame, the gas itself can be changed in several ways. The kinetic approach of ignition and combustion can be altered by non-thermal processes such as (i) the effect of ionic breeze caused by the passing of momentum via an electric field to an inert gas because of the space charge, (ii) an additional transition of ionized and energetic radicals that occur during gradient flow resulting from ion and electron drift in the electric fields, and (iii) the impact of electrons on excitation, dissociation, and ionization within the gas that generate radicals along with additional reactive species. Together or separately, these mechanisms can supply the extra combustion control required for a variety of applications, such as distributed ignition control in HCCI engines, ultra-lean flames, combustion in high-speed flows, cold, low-pressure environments such as high-altitude GTE relight, and detonating getting started in pulsed ignition engines.[102] At near-atmospheric pressures or greater, plasmas are often filamentary in form. Generally, the streamer breakdown technique is the one that starts a discharge. Fast-moving ionization fronts with a significantly elevated electric field at their ends and a decreased field across the cavity due to space charge phenomena are known as streamers. Radiation is produced extremely effectively by the streamer breakdown process because of the strong electric field at the streamer tip. When a streamer spans the discharge gap, a conductive channel is created, which causes the system to quickly heat up and have a high current.[103,104]

Aerospace engine combustor performance can be increased, the continuum of combustion consistency can be expanded, the temperature distribution unevenness at the combustor exit can be improved, fuel combustion efficiency can be increased, and pollutant emissions can be decreased through the use of plasma-assisted ignition (PAI) and plasma assisted combustion (PAC).[105] For supersonic propulsion systems, in particular, plasmas have demonstrated significant promise in enhancing the stability of high-speed ignition and combustion, enabling such systems to function with increased efficiency, stability, and power throughout a wide range of supersonic velocities. An investigation was carried out on a single-cylinder, four-cylinder, turbocharged gasoline engine's radio frequency (RF) plasma system contrasted under the same conditions with regard to a typical ignition coil. The addition of the plasma system increased the engine's lean limit of combustion and enhanced combustion stability under all operating circumstances, but it also increased nitric oxide (NO) emissions.[106] With Transient Plasma Systems, an ignition module that ignites the fuel/ air combination within the cylinder using extremely brief (nanosecond) plasma pulses takes the place of traditional spark plugs in an engine. The technology remained bench-tested at the time, but validation testing has demonstrated that it can boost fuel economy by up to 20% when installed in a conventional engine, so it's nearly ready for manufacturing now (Dan Singleton, Founder and CEO of TPS, 2019).[107]

DBD Plasma in Pollution Control

In highly industrialised and heavily populated regions, environmental pollution has become a very big problem and reached unacceptable levels. It is harmful to mankind as well as the entire biodiversity. Air and fresh water are necessary requirements to sustain a biological life. Now we are looking at the major aspects of water and air pollution and investigating them. Additionally, we evolve them and obtain clean drinking water and healthy air by using a variety of technologies. There has been an increasing amount of interest in using DBDs to destroy toxic chemicals and generally regulate pollution. Following Clothiaux et al.'s 1984 study on hazardous wastes from military operations, Since Fraser and Sheinson in 1986, further studies have been conducted to determine how volatile organic compounds (VOCs), such as hydrocarbons, chlorocarbons, and chlorofluorocarbons (CFCs), and nitrogen oxides and sulphur oxides, break down in quiet discharges.[108] Numerous industrial activities, such as chemical processing, print and paint shops, semiconductor fabrication, soil remediation, and water treatment, can contaminate exhaust air with gaseous hydrocarbons or organic solvent vapours.[109]

Free radicals, electrons, or UV photons may easily attack a lot of dangerous organic compounds. DBDs are employed for offering reactive elements such as $N_2^*(A^3\Sigma_u^+)$, $N_2^*(B^3\Pi_g)$, $O_2^*(a^1\,\Delta_g)$, O (^{1}D), O (^{3}P), H, OH, and N. These species, which were first created in the micro-discharge filaments by electron collisions, then provide a variety of reaction pathways that can produce more O, OH, or HO radicals: as reported in Equations 1 to 3.[110–112]

$$e^- + O^2 \rightarrow O^* + O^* + e^- \tag{1}$$

$$e^- + H_2O \rightarrow O^* + HO^* + e^- \tag{2}$$

$$O + H_2O \rightarrow HO^* + HO \tag{3}$$

Discharge plasma has been more popular in recent years for its ability to effectively breakdown and/ or remove dangerous chemical substances (such as pharmaceutical products and synthetic colours) and harmful microorganisms from wastewater and the gas mixture.[113,114] The plasma contains a strong electric field, charged particles with high energy, oxidising species (molecules and radicals), and reductive species (aqueous electrons, hydrogen atoms, and nitrogen atoms, among others).[115] When purifying polluted water, discharge plasma can have two distinct effects: electron collisions directly, as well as indirectly through ionic, molecular (H_2O_2, O_2, and O_3) and a collection of chemically active species produced in situ (*OH, O*, O_2*- and H*) through pyrolysis and photolysis processes.[116–118] Volatile organic compounds (VOCs) that are released into the atmosphere have the potential to negatively impact both the environment and human health. Among these are carcinogenic substances known as volatile organic compounds (VOCs), which also trigger photochemical reactions. According to current research, exposure to high levels of volatile organic compounds (VOCs) can have an assortment of negative short- and long-term consequences on human health, including altered neurological and cardiovascular function, higher death rates, and even the potential to cause cancer. Additionally, according to the WHO, VOCs significantly contribute to "sick building syndrome".[119–123]

As a result, the 1990 Clean Air Act Amendments of the United States mandated more stringent standards for VOCs emitted from industrial sources, acid rain, harmful air pollutants, urban air pollution, and localized haze and looked for a new methodology that had high efficiency in removing VOCs and other harmful compounds from air while also being inexpensive and simple to operate. The significant declines in annual mean b_{ext} and sulphate and nitrate levels are proof that the air is becoming cleaner as a consequence of the drastic reduction in SO2 and NO_x emissions brought about by the CAAA and changes in energy use (such as moving away from coal-fired power plants) brought about by economic and human activity.[124,125] Experimental research is being done on the destruction of formaldehyde (HCHO) molecules using dielectric barrier discharges (DBDs). HCHO was selected because of its chemical form, widespread presence, and possible health risks. Both "direct electron attack" and indirect gas-phase radical reaction processes are capable of destroying HCHO molecules. The dielectric barrier discharge reactor's gas composition, applied voltage, and gas residence duration are operating factors that impact the efficiency of HCHO destruction. With this approach, destruction efficiency may reach up to 97%.[126,127] The techniques using non-thermal plasma (NTP) provide an inventive way to address several environmental issues. The temperature of the electrons and other particles (ions, atoms, and molecules) in NTPs varies significantly.[128] There are many applications of different methods of plasma for pollution control in Table 2.

Table 2.Different Gas Discharge Plasma Configuration Using to Reduce Pollution

Plasma	Examples
Electron beam	Removal of SO_2 and NO_x, NO_x treatment using low-energy secondary emission electron gun, oxidative decomposition of aromatic hydrocarbons
Arc non-thermal plasma	For destruction of hazardous waste, modelling, plasma pyrolysis of medical waste
Electrostatic precipitators	Application in cement industry
Corona	Pulsed streamer corona, DC corona streamers induced by UV irradiation, scale-up for a coal-fired power plant, plasma-based total treatment of waste and low-grade fuels, kinetic analysis of non-thermal plasmas used for pollution control
DBD	NO_x, SO_2, VOCs (reviews)
High-frequency discharge	Oxidation of activated carbon and methane using a high-frequency pulsed plasma
Glow discharge	DC glow discharge in atmospheric pressure air as an essential source for pollution control
Microwave	Microwave-plasma discharge within the flue gas as a potential pollution-control method
Micro–hollow cathode	Applications for plasma chemical synthesis and pollution control become feasible.
UV	Pollution and odour control
Ozone	Ozone injection for NO control: numerical simulation, removal of sulphur dioxide and nitrogen oxides, effect of ozone injection on the catalytic reduction of nitrogen oxides

SD (Silent Discharge) CO_2 Laser

The gas discharges are employed in laser applications—more precisely, called gas lasers. There are many different types of gas lasers, but they all have the same feature: gas discharges always serve as the framework of population inversion, which is required for laser activity. A glass discharge tube with mirrors at either end holds the gas within at lower pressure. It is possible to arrange the anode and cathode at the tube's two ends.[129]

Today, high-power CO_2 lasers are widely pumped using dielectric-barrier discharges. Ishchenko (1978) and Christensen, 1979 were most likely the first to employ laser pulses and pulsed DBDs to produce CO_2.[130,131] Just two years later, Yagi and Tabata introduced the idea of a high-power quasi-DC CO_2 laser driven by DBDs, a group that might expand on its ozone-generating expertise.[132] The CO_2 laser is a molecule laser. This silent discharge (SD) CO_2 laser quickly rose to prominence as the most successful material processing commercial laser available in Japan. This high-power infrared laser (λG10.6 µm) quickly achieved commercial fulfilment when it was employed for thick metal plate precision welding and cutting. The SD laser employs relatively low frequencies between 50 kHz and 200 kHz, in contrast to other commercial high-power CO_2 lasers that operate at 13.65 MHz or 27.3 MHz. The low frequency has the benefit of allowing the glass or alumina dielectric layers on the electrodes to efficiently restrict and stabilize the discharge current. The glass or alumina dielectrics covering the water-cooled planar metal electrodes are spaced 20 to 50 mm apart. To remove heat and stabilize the discharge, a high-velocity crossflow moves across the discharge gap at a speed of 50 to 80 m/s. The low operating pressure (6.4 kPa) and high helium content in the laser gas combination (CO_2/N/He = 1/8/4) provide the appearance of an evenly distributed discharge. There is not enough time while operating at 160 kHz for the ions to decay or be swept off between subsequent half periods. Consequently, the discharge exhibits characteristics akin to those of a resistive load (ion trapping discharge). With output levels up to 5 kW, almost diffraction-restricted infrared light at the wavelength 10.6 µm is achieved. The effectiveness is more than 10%.[5,84,133]

The CO_2 laser uses a combination of He, CO_2, and N_2 in a low-pressure DC discharge (from 266 Pa to 1330 Pa) as well as DBDs (from 5 kPa to 100 kPa). Using optical emission spectroscopy, the vibrational temperature was measured in both discharges, and the results revealed comparable qualitative behaviour. Due to the distinct characteristics of the discharges under study—particularly the DBD's reduced neutral gas heating—the vibrational temperature of nitrogen in the DBD was nearly double that of the DC glow discharge.[134–136] There is a laser transition between CO_2 vibrational energy levels. N_2 vibrational levels are used in a two-step method for excitation. This laser has an extremely high efficiency (usually 30%). The low energy required for excitation (only a few eV, as opposed to 20–30 eV for the He–Ne and Argon ion laser) accounts for the high efficiency. In addition, the excited levels of N_2 are meta-stable, guaranteeing effective energy transfer to CO_2. Helium's use as the buffer gas improves efficiency even more by, for example, turning off the lower laser levels, which improves population inversion.[137] Nitrogen is added to discharge plasma to modify the composition of the laser-active medium and enhance the laser's thermodynamic properties. Nitrogen addition dramatically lowers the amounts of C atoms produced in the plasma-chemical reactions of laser discharge as well as the CO dissociation level.[138] When an electric field is provided, carbon dioxide and other auxiliary gases, such as nitrogen and helium, are combined to form the primary operational environment of CO_2 lasers. This mixture generates a laser beam with a wavelength of 10.6 µm. As a result, after absorbing laser energy, CO_2 lasers quickly raise the temperature of the radiated material, which causes the surficial material to evaporate during the ablation procedure.[139] With its high laser energy strength, wide laser beam radiation area, and affordability, CO_2 lasers are generally utilized in the laser welding and cutting industries, medical surface treatment, etc.[140,141,142] Stainless steel 430's wet ability was investigated using a commercial CO_2 laser engraver, and it was successful in creating nano-structured omniphobic and superomniphobic surfaces.[143,144]

Incoherent Excimer Ultraviolet Sources

As was previously noted, a micro-discharge's plasma may be described as a momentary high-pressure glow discharge. The plasma conditions in a micro-discharge channel of a dielectric-barrier discharge operating in rare gases or a rare gas/ halogen combination are comparable to those found in pulsed excimer lasers. Excimers that emit high-intensity UV light are well suited for the efficient stimulation of dielectric-barrier (silent) discharges. It is possible to get the xenon molecular continuum at 172 nm with an efficiency of around 10%.[145] Each micro-discharge can therefore function as a powerful source of vacuum ultraviolet (VUV) or ultraviolet (UV) radiation. High collision rates, which call for high pressure, and effective excitation or ionization of precursor species, which call for a non-equilibrium discharge, promote the creation of excimers. These two needs are readily combined by DBDs. Common instances include the creation of Xe or XeCl excimer complexes, wherein one is mostly produced by recombination of ions and the other primarily from neutral excited atoms. The most important reactions are the following:

$$e + Xe \rightarrow e + Xe^{*}\,(^{3}P_{1'2}) \tag{4}$$

$$Xe^{+} + Cl^{-} \rightarrow XeCl^{*} \tag{5}$$

$$Xe_2^{*} \rightarrow Xe + Xe + \text{VUV radiation} \tag{6}$$

$$XeCl^{*} \rightarrow Xe + Cl + \text{UV (308 nm)} \tag{7}$$

The capacity to efficiently convert electron kinetic energy to electronic excitation energy and quickly direct that excitation to a few low-lying atom and excimer levels is a unique property of high-density rare gases at atmospheric pressure or beyond. Because UV/ VUV photons may disrupt most chemical bonds, sources that generate these photons in the 5–15 eV energy range have found many fascinating uses.[146] There is a variety of technologies to further ease use. Here we focused on excimer lamps or lasers, and the UV sources.

Excimer Lamps

Excimer production can be induced in dielectric-barrier discharges because the plasma conditions in the micro-discharges are similar to those of high-pressure glows.[147] Lamps that emit light spontaneously due to excimer production can be powered by dielectric-barrier discharges, microwave discharges, pulsed or DC longitudinal discharges, or pre-ionized pulsed transverse discharges. It is the xenon excimer lamp that is by far the most significant exemplar. It achieves 40% efficiency. It is possible to convert its VUV radiation to visible light using phosphors. This wavelength adjustment is used in flat screens that illuminate liquid crystal displays, mercury-free fluorescent bulbs, and flat plasma display panels with image diagonals up to 1.5 meters. By turning on internally applied phosphor layers, xenon VUV light in small addressable DBD cells with 0.1 mm electrode spacing and 0.2 mm width is transformed into red, green, or blue picture dots. Gas mixtures at 50–70 kPa pressure that comprise 5–10% Xe in Ne or He are used. Operational voltage is limited to 200–300 V.[46] The last ten years have seen a rise in the use of pulsed light sources, especially in excilamps, to produce incoherent ultraviolet (UV) and vacuum UV radiation. The excilamp is a gas-discharge UV and VUV radiation source that uses excimer or exciplex molecules' non-equilibrium spontaneous radiation as its basis.[148] Excilamps are distinguished from luminescent and thermal radiation sources by their very narrowband radiation spectra.[149]

Dielectric-barrier (the range of possible geometries, plane or cylindrical, makes the new UV sources an attractive choice for many photophysical and photochemical applications) excilamps and capacitive discharges—in which the current flowing is limited by a dielectric—are the most alluring UV and VUV sources of spontaneous radiation. Because the functioning gas combination does not come into touch with the metallic electrodes, these lamps have a long lifespan. Research has shown that a broad range of average energy and electron concentration in a discharge gap may be operated within barrier-discharge lamps. Due to this outcome, the selection of the dielectric barrier material as well as the variation in the initial electric field intensity in the gap. The working mixture's composition, pressure, and the excitation electrical pulse's rising time all affect how long a radiation pulse lasts. The formation of diffuse cone-like micro-discharges produces the highest radiation power.[150–152] Gas discharge plasmas serve as the basis for many kinds of light sources. We shall divide the upcoming discussion into two categories: traditional "electroded lamps" and the more modern "electrode-less discharge lamps." There are high-pressure, thermal LTE lamps (like high-intensity discharge (HID) lamps) and low-pressure, non-LTE lights (like fluorescence lamps) in each category as mentioned in Table 3.[129]

UV Radiation

Although it is invisible to the human eye, ultraviolet light, which falls between 100 and 400 nm in wavelength, is a crucial part of sunshine. It is commonly recognized that UV radiation from plasma sources affects living things differently. The UVA (320–400 nm), UVB (280–320 nm), and UVC (100–280 nm) portions of the UV spectrum are separated.[153] The earth's ozone layer blocks all UVC and some UVB radiation. Ordinary air blocks shorter wavelengths. UVA radiation makes up 95% of all UV radiation that reaches Earth. The depth of light penetration into human skin increases with wavelength. On the other side, a longer wavelength results in a reduced risk to biological systems. Both UVA and UVB may pass through the epidermis, and UVA can even penetrate the dermis. These wavelengths can interact with endogenous chromospheres and photo-sensitizers; this may result in the production of reactive oxygen species and lipid, protein, and DNA damage. Additionally, UVB can directly interact with DNA to produce photoproducts called dipyrimidines. Sunburn (erythema) and the promotion of pigment production are two short-term impacts of UV exposure. Chronic and overly high UV irradiation, which is mostly caused by UVA radiation, changes the structure of the corneal connective tissue and causes wrinkles or premature skin ageing. Furthermore, it is recognised that exposure to UVB and UVA rays can cause skin cancer.[154–156] Table 4 shows the applications of excimer lamps and the UV sources.

Table 3.Different Types of Lamps with Their Properties and Applications

Types of Lamps	Properties and Applications
Electroded low-pressure lamps	Electroded low-pressure non-LTE lamps, known as fluorescent lamps, work in the positive column of D.C. glow discharges using a combination of a rare gas and mercury, which may be found in both liquid and gaseous form. According to estimates, fluorescent lighting makes up over 80% of artificial light in the globe.
Electroded high-pressure lamps	High-pressure electrode lamps, commonly referred to as HID (high-intensity discharge) lights, function within the framework of an arc discharge. Usually, the pressure is a few atm. Technically speaking; the high-pressure mercury (HPM) lamp was the first HID light. It generates visible light without requiring the use of phosphors. In fact, under these high-pressure circumstances, the UV light (254 nm), which is mostly present at low-pressure settings, is reabsorbed.
Electrode-less lamps	There are currently manufactured electrode-less lamps that may be activated by four different types of discharge mechanisms: travelling wave discharges (SWDs), microwave discharges, capacitive or e-discharges, and inductive or H-discharges.
Electrode-less low-pressure lamps	The electrode-less ICP lamps—where the energy is inductively connected to the discharge plasma—are the most well-known and exclusive varieties of electrode-less low-pressure fluorescence lamps available for purchase. An RF current with a frequency of 2.65 MHz, which is inside the lighting-permitted range, ignites the discharge. The "QL lamp" from Philips and the "Genura lamp" from GE Lighting are two examples of this setup seen in stores.

Electrode-less high-pressure lamps	A microwave HID resonant cavity lamp is the only electrode-less high-pressure, or HID, light available for purchase. Microwave power is connected to the discharge through a resonant cavity that houses the discharge tube. Only one commercial lamp of this kind—the Fusion illumination “Solar 1000”—was utilized for general illumination.

Table 4.Listed Versatile Applications of Excimer Lamps and UV Sources

Sources	Applications
Excimer lamps	Surface modification, surface coating, plasma displays
UV sources	Sterilisation, ozone generation or water cleaning, surface treatment and thin film deposition, medical most of the dermatology (surface modification, therapeutic application, biomedical decontamination, skin cancer)

DBD Plasma in Photonics

The science and technology of producing, directing, and detecting photons—which are electromagnetic radiation waves that include visible light as well as infrared and ultraviolet radiation—is known as photonics. The fundamentals of the physics behind several light-emitting plasmas, such as those found in lasers, microcavity plasmas, and ‘conventional’ light sources like fluorescent and thermal arc lamps, will be covered. The electron number density, operating pressure, specific power deposition, gas phase chemistry, background gas temperature, and wall interactions of these visible, UV, and VUV sources vary greatly, so the focus will be on the basic mechanisms underlying the operation of plasma photonic systems and devices. Apart from its role as a light source, plasma may also act as a carrier for the transmission or modulation of electromagnetic waves. This is explained by the collective motion of free electrons that are circulating among atoms and molecules in plasma, as contrasted with photon emission that results from atoms and molecules’ trapped electrons shifting from higher to lower energy levels. When using a low-temperature plasma, the frequencies for EM-wave manipulation that these plasma media have successfully produced in prior experiments vary from radio frequency waves to millimeter waves, with the possibility of reaching the infrared. Here, plasma media via functional forms are referred to as plasma metamaterials and this word is defined more broadly to include functional designs that are altered in accordance with EM and optical physics, a couple of the most active fields nowadays in physics. Research is ongoing to make plasma photonic crystals in 1D, 2D and 3D configurations. Through a meshed dielectric barrier discharge, tunable superlattice plasma photonic crystals are produced. These thin artificial lattices and thick self-organized lattices make up these plasma photonic crystals, which are readily tunable by varying the applied voltage. The creation of square, superlattice, and hexagonal PPCs by self-organized filaments in dielectric barrier discharges was exploited to create filters with spectral properties that can be controlled both spatially and temporally, leading to advancements in PPCs and the construction of tunable filters. Band gaps may be constructed for the TE mode at frequencies exceeding 100 GHz with lattice constants as tiny as 1.7 mm in the case of the hexagonal crystal structure. This material or annular plasma photonic crystals are a useful platform for a range of applications and provide new capabilities.[157–161] DBD plasma provides several uses in photonics:

Light Sources

Photons can also be produced by DBD plasma. A gas inside a dielectric barrier may produce plasma when a high voltage is applied, which releases light. This emission may be regulated and used in a variety of photonics applications, including optical sensing, fluorescence excitation, and customized lighting. A collection of dielectric barrier discharges (DBDs) produced within cavities in aluminum screen, any arrangement woven with Al wire, or aluminum foil, for example, that has been chemically treated to produce a film on the outside of nonporous alumina, was the “engine” of the initially developed lamps. From the beginning, micro-plasma lamps were intended to produce visible light by the down-conversion of plasma-produced UV radiation in a coating comprising a mixture of phosphors. Their efforts were directed towards facilitating the creation of flat lamps.[162]

Plasma Assisted Processing

Materials may be modified for photonics applications using DBD plasma. It can be used, for instance, on materials’ surfaces to enhance their optical qualities or to the formation of microstructures for photonic devices such as diffraction gratings or waveguides. Dense plasma referred to as plasma mirror is created when a powerful ultrashort laser pulse strikes an optically polished substrate. This plasma mirror can reflect the remaining incident beam and functions as an active optical element, producing high-order harmonics of the incident frequency in the reflected beam’s spectrum.[163]

Optical Modulation

It is possible to modify the characteristics of light travelling through plasma. Modulating the parameters of the plasma discharge, such as the gas composition or applied voltage, allows one to alter the medium’s absorption properties or refractive index. Applications like modulation or optical switching can take advantage of this feature.[164]

Plasma Assisted Deposition

Using a process called plasma-enhanced chemical vapour deposition (PECVD), thin films may be deposited on substrates. PECVD can be used in photonics to deposit coatings with certain optical characteristics, including dielectric mirrors or anti-reflection coatings. By using DBD plasma, the deposition process may be improved, and layer thickness and composition can be precisely controlled. The flexible hybrid electronics sector is particularly interested in printed electronics on low-temperature substrates like paper because they may be used in biocompatible and disposable electronic applications as well as consumer electronics, wearable, and packaging. Aerosolized nanoparticles are focused onto a target substrate using dielectric barrier discharge plasma in plasma-jet printing. The printed material's characteristics may be altered using the same plasma, and it can even sinter in place. The technology's gravity-independent plasma-assisted deposition makes it applicable even in microgravity and space conditions.[165]

Optical Sensing

A sensitive medium for the detection of electromagnetic radiation involves plasma. It is possible to identify and exploit changes in the plasma's characteristics brought about by photon contact for a variety of sensing applications, including spectroscopy and imaging.[166] All things considered, DBD plasma has flexible properties that may be used to create novel photonics technologies for anything from thin film deposition and optical detection to light sources and optical modulation. Integrated circuits and optical components are two examples of photonic devices that are made using plasma etching. With the use of plasma, materials on a substrate may be removed selectively, allowing for the exact patterning needed for photonics applications.

DBDs as Energy Sources

Dielectric Barrier Discharge (DBD) plasma's capacity to effectively produce reactive species and modification surfaces has attracted attention in several energy-related applications. Dielectric Barrier Discharge (DBD) plasma is not as widely employed for large-scale energy generation as nuclear or fossil fuels, but it is still a viable source of energy that may be investigated. Nonetheless, studies and trials are still being conducted to fully utilize its energy-generating potential. DBD plasma may be an energy source in the following ways:

Plasma Assisted Combustion

Enhancing combustion processes with DBD plasma can result in cleaner and more efficient energy generation from fossil fuels. It is feasible to enhance ignition, boost flame stability, and lower pollution emissions by exposing the fuel-air combination to plasma. Applications using this kind of innovation in the manufacturing sector of heating, transportation, and power generation are being investigated.

Plasma Assisted Water Splitting

A procedure known as plasma electrolysis can be performed with DBD plasma to split water molecules into hydrogen and oxygen gases. This method of producing hydrogen has the potential to be a clean, sustainable energy source for fuel cells and other uses. One of the renewable energy sources soon is anticipated to be hydrogen. The only significant waste product of burning hydrogen is water vapour. It is anticipated that the energy conversion efficiency to electricity using fuel cells would be between 60% and 80%. Except for nuclear energy systems, this is one of the finest clean energy sources with high conversion efficiency.[167] We write here the water-gas shift equation;

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (8)$$

Plasma Assisted Gasification of Biomass

Synthesis gas (syngas), a combination of hydrogen and carbon monoxide, may be produced by gasifying biomass feedstock using DBD plasma. Hydrocarbon is the initial gas used in breakdown. The process is self-sufficient, save from the plasma discharge's need for electricity. Hydrogen and other materials, including carbon black, are the two primary products that are created during the pyrolysis of hydrocarbon feedstocks; however, in certain processes, CO and/ or CO_2 are also produced. However, the majority of the occurrences that have been documented thus far have included the discharge of a minor number of hydrocarbons that are combined with other substances, such as water vapour or N_2, meaning that the amount of hydrogen produced is not necessary. Syngas are a useful fuel for power generation and may also be utilized as a starting point for the synthesis of chemicals and liquid fuels.[168] Breakdown equations are the following:

$$CH_4 \rightarrow C + 2H_2 \qquad (9)$$

$$C_3H_8 \rightarrow 3C + 4H_2 \qquad (10)$$

Direct Conversion of Plasma Energy

There are situations where DBD plasma itself can be used to produce power directly. For instance, certain plasma devices can create electrical discharges that may be used to create electricity. To increase the effectiveness of these systems, more study is necessary as their present efficiency could be restricted. In order to directly synthesize liquid chemicals (alcohols, acids, and hydrocarbons) and syngas from CO_2 and CH_4 at atmospheric conditions, a plasma-catalytic reactor was created. This reactor consists of a vertical coaxial dielectric barrier discharge reactor loaded with solid catalysts. Furthermore, adding voltage to create a plasma discharge is simple, produces few emissions, and provides a different method of storing renewable energy.[169] DBD plasma is a green energy or environment-friendly energy source. Although these applications seem promising, it's crucial to remember that DBD plasma-based energy technologies continue to be in the early stages of research and development, and before they can be extensively used as mainstream energy sources, there are issues with efficiency, scalability, and cost-effectiveness that need to be resolved.

Summary and Outlook

Dielectric barrier discharges have found extensive use in industry and, more recently, have seen a significant rise in market penetration. This tendency will undoubtedly continue. There are several explanations for this theoretically ancient gas discharge's resurgence. Modern modelling and diagnostic technologies have undoubtedly improved our understanding of the underlying mechanisms influencing discharge initiation and the subsequent plasma chemical reactions. With the development of novel plasma sources and the recent enormous advancements in our knowledge of physical plasma processes, there is an increasing emphasis on the use of non-thermal dielectric barrier discharges (DBDs). A non-thermal plasma known as a Dielectric Barrier Discharge (DBD) is produced when two electrodes that are separated by a dielectric substance and are filled with gas at atmospheric pressure collide. This study offers a thorough analysis of DBD, encompassing its underlying ideas, workings, and applications. Industrial applications frequently employ dielectric barrier discharges because they are a simple way to create the appropriate non-equilibrium conditions. The streamer breakdown process produces a filamentary discharge that produces high-kinetic-energy electrons, while the heavier particles stay at room temperature. The supply gas combination and the applied pressure determine the plasma's composition and characteristics. Additional benefits of DBDs include their inexpensive nature and effective scalability through numbering-up. Many plasma-catalytic processes are being studied at this time. Utilizing air plasmas at atmospheric pressure to oxidize volatile organic molecules sheds light on the principles behind plasma catalysis. This review covers the challenges and future directions in DBD research and technology development, including scalability and reactor design optimization. In general, researchers, engineers, and practitioners interested in delving into and making use of DBD technology will find this review to be a useful resource.

Conflict of Interest:

The corresponding author, on behalf of all the authors of the submission, discloses that there are no financial and personal relationships with other people or organizations that could inappropriately influence (bias) this work.

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