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Plasma Technologies: A Sustainable Frontier for Environmental Conservation

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Abstract

Plasma naturally exists throughout the universe, and recently, mankind has realized its vast technological applications. The scope of current plasma physics experiments has produced several well-established industrial applications in addition to several exciting new ones. This review aims to give a basic overview of the area of plasmas and the role plasma physics plays in current scientific endeavors to the broader scientific and technological community. This paper describes the benefits of plasma technology to humankind in various fields, including medicine and engineering disciplines like mechanical, chemical, and electrical. The technological applications include materials processing like semiconductor manufacturing, surface treatment, lighting, cutting by plasma, and plasma etching. Also, the various environmental applications of plasma as a roadmap to environmental sustainability are discussed. The possibilities for plasma physics in the future are summarized in conclusion.

Keywords: Plasma, crystals, semiconductors, fusion, power, polymers.

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1. Introduction

An exciting and energetic form of matter, plasma, noted as matter's fourth basic state, naturally exists throughout the universe. Unlike solids, liquids, and gases, plasma consists of charged particles, like electrons and ions [1,2]. Plasma forms when the gas is heated to a very high temperature (6000–10,000 K) or when the gas is subjected to strong electromagnetic fields, leading to the ionization and separation of the atoms into positively charged ions and negatively charged electrons [3]**.** Natural examples of plasma include lightning, auroras, and the Sun's surface. Artificial plasma is generated in devices like plasma torches, fluorescent lights, and plasma TVs [4,5,6,7]. Many scientists are currently focusing on the production of plasma artificially, including the potential benefits it might provide humanity.

Humans have witnessed plasma in nature for a very long period. It is now known as matter's fourth basic state [8]. According to astrophysical research, the majority of galaxies are found to be made of this substance. A medical scientist named Purkinje (1787-1869) first used the term "plasma," but he was referring to the clear liquid that remains after various corpuscle components and protoplasm are extracted from the blood. This was not the plasma now understood to be the fourth basic state of matter. First identified by William Crooks in 1879, "plasma" was not given its current name until 1928, when Irving Langmuir coined it. Langmuir theorized the existence of a boundary layer, or plasma sheath, between solid particles and ionized plasma [9,10,11]. He also found periodic electron density fluctuations in specific sections of a plasma discharge tube called Langmuir Waves. Because of this, the field of plasma physics was born.

The use of plasma has grown substantially due to the technology's expanding benefits and potential. The unique properties of this high-energy matter are tapped into by plasma technology for various uses. Nuclear fusion reaction as a future energy source is one of them [12,13]. Scientists are working tirelessly to achieve controlled nuclear fusion, which replicates the Sun's energy source, to provide clean and virtually limitless power for our world [14,15].

This review paper focuses on i) discussing plasma properties and detailing technological applications. ii) the advancements, findings, or innovations in the plasma field. iii) The paper also focuses on plasma's environmental and agricultural applications, which will help readers understand how plasma technology helps humanity maintain a sustainable and eco-friendly future.

2. Plasma Technology and its Applications

Plasma technology is a dynamic discipline, combining possibilities and innovation [16]. It is concerned with the research and application of plasma. Plasma sparks a bright future for various industries and scientific breakthroughs, from lighting up the globe to sending humanity into space. The definition of plasma depends on several parameters, such as temperature, ionization level, size, density, and model assumptions [17,18,19]. The principal types of plasma and their properties are as follows:

a) **Hot plasma (thermal plasma):** Thermal plasma is generated using direct current (DC), alternating current (AC), radio frequency (RF), or microwave sources at temperatures between 2,000 and 20,000 K. It is created at high pressures (greater than 10 kPa) [20] and it has charged particle number densities in the range of 10^{19}-10^{21} per m^3 [21].

b) **Cold plasma (non-equilibrium or non-thermal plasma):** Low-pressure plasmas containing high electron temperatures and low neutral and ion temperatures are termed cold plasmas [22]. Cold plasma, or plasma generated at lower temperatures with a lower plasma density—typically less than 1%, or around 100 million electrons per cubic centimeter—is the type of plasma produced in the surface treatment industry [23].

c) **Ultracold plasma:** The limits of conventional neutral plasma physics are pushed by ultracold neutral plasmas. Their ion temperatures are around 1 K, while their electron temperatures range from 1 to 1000 K [24]. Many atomic systems, such as Xenon, Caesium, Rubidium, Strontium, and Calcium- any atom that can be readily laser cooled and has a suitable laser wavelength for photoionization can produce ultracold plasmas [25].

d) **Fully ionized plasma:** A plasma that has been fully ionized and has an ionization degree close to 1 [26]. The Solar Wind (interplanetary medium), stellar interiors (the core of the Sun), and fusion plasmas are a few examples [27].

e) **Weakly (Partially) ionized plasma:** A partially ionized plasma with an ionization degree of less than 1. The ionosphere (having ionization degree 2×10^{-3}) and gas discharge tubes are two examples [26]. The atmosphere of the Sun, molecular clouds, the interstellar medium, accretion disks, planet ionospheres, cometary tails, and many other astrophysical environments are composed primarily of partially ionized plasmas, whose ionization degrees can range from extremely weak ionization to almost complete ionization [28].

f) **Collisional and non-collisional plasma:** A plasma that often experiences collisions between its charged particles—ions and electrons—is called a collisional plasma. In comparison, particles in collision-less plasmas are less dense and interact with each other far less frequently [29]. Compared to collision-less plasmas, collisional plasmas are typically denser and colder [30].

g) **Neutral and non-neutral plasma:** Ionizing collisions between particles produce ions and electrons from atoms and molecules in a standard neutral plasma. Neutral plasmas often have temperatures of thousands of Kelvin or more because the average ionization potential is on the order of one electron volt [24]. A non-neutral plasma is a many-body collection of charged particles with no overall charge neutrality. Non-neutral plasmas have a wide range of applications, including coherent radiation generation in free electron devices, such as free electron lasers, magnetrons, and cyclotron masers; the propagation of intense charged particle beams in periodic focusing accelerators and transport systems; strongly-coupled one-component plasmas and Coulomb crystals; quantum computers; trapping of antimatter plasmas and production of anti-hydrogen [31,32].

h) **Magnetic and non-magnetic plasma:** When the surrounding magnetic field is strong enough to change particle trajectories noticeably, the plasma is said to be magnetized. Specifically, magnetic plasmas have strong anisotropy, exhibiting distinct responses to applied forces perpendicular to and parallel to the direction of the magnetic field. A laboratory plasma is the clearest example of a magnetized plasma [33].

A plasma with a weak or negligible magnetic field is said to be non-magnetized. In this scenario, the magnetic field does not affect the mobility of the charged particles (ions and electrons). Instead, collisions with other particles and electric fields regulate their motion most of the time [34].

i) Low, medium, and high-density plasma: The concentration or count of ionized gas particles in a specific volume is called the plasma density. This is also occasionally used to discuss the proportion of ionized gas in a volume. The qualities of plasma are dependent on the density since it can fluctuate. A very mildly ionized gas with a very low plasma density is nevertheless considered plasma and has plasma properties. A hot plasma has a density of around one trillion electrons per cubic centimeter and is fully ionized [35]. It is the kind of plasma related to astrophysics.

A plasma is categorized as high density if its particle density (N) is greater than or equal to 10^{15-18} cm^{-3} and low density if it is less than or equal to 10^{12-14} cm^{-3}. High-density plasma produced by capacitively connected and inductively coupled is frequently used for decontaminating plasmas, etching in microelectronics, and manufacturing nanomaterials. However, the Wakefield accelerator uses low-density plasmas [36].

j) Grain and Dusty Plasmas: An ionized gas with dust particles ranging from tens of nanometres to hundreds of microns in size is called a dusty plasma [37]. The dust grains get charged by interacting with the plasma and surrounding environment. They might have a spherical, rod-like, or irregular pancake form. They could be made of conductive or dielectric materials, such as SiO_2 or Al_2O_3. The particles might be fluffy ice crystals or even liquid droplets, though they are usually solid. Usually, they have a significantly higher mass than the ions and electrons in plasma [38].

Proto-planetary and solar nebulae, molecular clouds, supernova explosions, the interplanetary medium, circumsolar rings, and asteroids are a few examples of the ubiquitous dusty plasmas in the cosmos. Planetary rings (such as those of Saturn and Jupiter), the atmosphere of Mars, cometary tails and comae, lunar dust clouds, and so forth are features found in our solar system [39]. Both noctilucent clouds and polar mesospheric summer echoes, clouds of minuscule (charged) ice particles generated in the summer polar mesosphere at altitudes of around 82-95 km, are found close to Earth. The area around artificial satellites and space stations is also home to dust and dusty plasmas. It also turns out that dust is frequently found in laboratory plasmas, used in tokamaks and semiconductor fabrication [39].

k) **Liquid, colloidal, and plasma crystals:** Colloidal plasmas can "condense" into liquid and crystalline phases while maintaining their fundamental characteristics in specific situations. New states of matter, such as "liquid plasmas" and "plasma crystals," are consequently produced by this "plasma condensation" [40].

Complex plasmas, filled with solid particles in the nanometre to micrometer range, can produce both liquid and crystalline phases. The particles charge negatively up to a few volts because of absorbing ions and electrons. Because of their considerably greater mass than electrons and ions, the particles control the most fundamental level of plasma processes, known as kinetic level observation. Particle clouds have the potential to develop both crystalline and fluid shapes because of the strong Coulomb interaction among the particles, termed plasma crystals [41].

2.1 Applications of Plasma Technology

Applications of plasma technology are numerous. A few noteworthy examples of plasma technology's applications, along with recent advancements and findings, are given below:

a) **Material processing:** Plasma can be highly energetic and can also be precisely controlled to create specific effects, making it a versatile tool for numerous material processing applications. Plasma cutting and welding are commonly used in metalworking industries. Many of the world's top manufacturing companies rely heavily on plasma processing technologies. The electronics sector, in particular, relies on plasma-based technologies to produce very large-scale integrated microelectronic circuits. Plasma material processing is also essential in various industries, like aerospace, automotive, steel, biomedical, and toxic waste treatment. Plasma processing technology is increasingly used in new technologies such as diamond and superconducting film growth [42].

The plasma processing technology is crucial in creating modern semiconductor devices because it influences the material properties, cleanses surfaces, and ensures precise control of integrated circuit (IC) fabrication throughout the wafer cleaning and etching stages. Plasma/gas-based semiconductor technologies have significant potential in electronics, especially for manufacturing sophisticated devices with expanded capabilities. These techniques are mostly used to manufacture thin films of semiconducting materials, which are used to produce various electronic devices such as transistors, solar cells, and light-emitting diodes [43]. Compared to traditional implanters with more complex designs, the plasma immersion ion implantation (PIII) technique offers the advantages of high dose-rate implantation at low energies and vast area processing capacity. PIII has been used in semiconductor manufacturing for impurity gettering, poly doping, and the creation of shallow junctions, among other uses [44]. In addition, pulsed plasmas have the potential to produce less structural, electrical, or radiation (such as vacuum ultraviolet) damage, as well as a greater etching rate and improved uniformity. Additionally, undesirable artifacts in etched micro-features, such as aspect ratio-dependent etching, micro-trenching, notching, and bowing, can be reduced using pulsed plasmas. Because of this, pulsed plasmas might be essential for etching the next generation of microdevices, which will have distinctive feature sizes in the sub-10 nm range. Employing power-modulated (pulsed) plasmas may resolve some of the challenges of creating nano-devices with a sub-10 nm range [45]. The process of plasma cutting through square tube steel is displayed in Figure 1.

Figure 1: Plasma cutting through square tube steel (http://tinyurl.com/5b6c9z6f. Retrieved January 11, 2024).

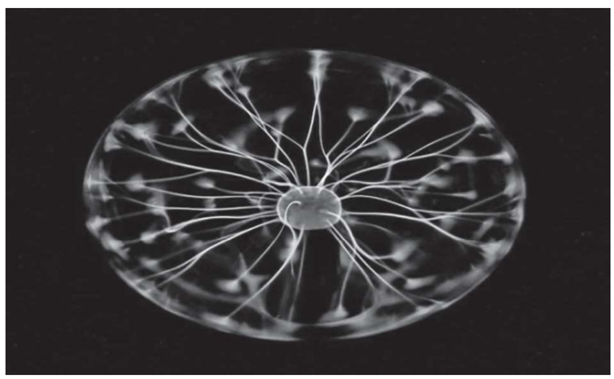

Figure 2: Glowing neon blub in shape of lightening (http://tinyurl.com/mv5d82bz. Retrieved January 11, 2024).

b) **Medicine and Healthcare:** "Cold plasma," typically near room temperature, holds immense potential for various medical applications. Plasma sterilization is vital in medical sciences. The use of low-temperature plasma can effectively sterilize medical equipment, ensuring the safety of patients [46]. For example, non-thermal plasma can be used for dental whitening. Plasma medicine is a rapidly evolving field with immense potential to revolutionize healthcare. As research progresses, more clinical applications are expected to emerge, offering new hope for treating various medical conditions.

A multidisciplinary field of research known as "plasma medicine" looks into the applications of plasma in the healthcare industry. Research on non-thermal plasma technology primarily concentrates on atmospheric pressure applications, known as non-thermal atmospheric pressure plasma or "NTAPPs" for short. Direct uses of NTAPP include:

- Air purification.
- Food industry applications (such as decontaminating food and food contact surfaces).
- Medical and dental applications [47].

More germs are killed by cold plasma than by antibiotics. Many ecologically favorable particles (NO, O_3, OH^-, O^{2-}, H_2O_2, UV radiation) are produced during the cold plasma therapy of wounds, and these particles remove biologically hazardous contaminants such as microbial organisms and chemical toxicants [48]. Over the past nine to ten years, cold atmospheric plasma (CAP) has become an adequate method for producing and delivering regulated doses of reactive species to cancer cells in vitro and in vivo [49]. Thus, plasma oncology, or the use of plasma in cancer treatment, is an emerging area of research in medical sciences. Prospects and challenges for plasma medicine in the future will primarily focus on optimizing and controlling CAP devices, expanding their medical applications, and creating new avenues for plasma-based therapeutics [50,51]. Numerous medical fields have come across the direct medical applications of CAP. Dentistry, neurology, oncology, and infection control are a few examples of these fields.

Conversely, the indirect uses of CAP are performed utilizing a mixture (like a stem cell niche), a liquid item (like plasma-activated medium), or a solid object (like a surgical implant). The biomedical effect of CAP flows through cellular, protein, and even DNA/mRNA levels, regardless of the operating mode [52,53]. Presently, plasma biological interactions are combined with direct irradiation techniques for plasma discharges that encounter biological surfaces, such as skin and teeth. Plasma-liquid interactions are the foundation of indirect methods utilizing liquids treated with plasma. Preclinical research and cancer therapy often use both these two techniques. By comprehending the interplay between plasma and living things, the authors of

Ishikawa et al.[54] discuss possibilities for future advancements in cancer therapy applications. Using in vitro, ex vivo, in vivo, and direct application techniques, the review by *Koga-Ito et al.* [55] evaluated the effectiveness of CAP and plasma-activated liquids against viral-based illnesses. Remarkable advancements were noted in dentistry, cancer treatment, and wound healing [55]. A review of the application of multi-stream creep plasma generator design for antibacterial and therapeutic purposes has been discussed by *Kolomiets et al.* [52].

c) **Lighting:** Plasma lighting technologies like fluorescent and neon lights use ionized gases to produce high-intensity illumination. Compared to conventional incandescent lamps, they use less energy and last longer [56]. Figure 2 showcases the radiations associated with a neon bulb.

The phosphor coating on the wall transforms the ultraviolet light produced by the plasma in a fluorescent lamp into visible light [57]. The effectiveness and lower carbon footprint of a lighting system based on mercury lamps are advantages from an environmental perspective; the toxicity of mercury is a disadvantage. The prohibition on mercury in vehicle headlight plasma lamps has sparked the development of substitute mercury-free plasma light sources, which have replaced high-pressure street lighting bulbs [58]. Energy-efficient bulb development is crucial, and the lighting sector is working towards this goal. Furthermore, more electrodeless lamps—which get their power indirectly rather than through cables attached to internal electrodes—and lamps with less or no mercury are among the new and enhanced plasma-based lamp types [59].

d) **Aerospace:** Plasma thrusters are used in spacecraft for propulsion. These thrusters ionize gases like xenon and expel them at high speeds to generate thrust, making them highly efficient for long-duration space missions [60]. For example, plasma spray coating (PSC) technology has been advanced to safeguard the surfaces of vital parts in aircraft and spacecraft landing gears and jet engines [61]. Between the 1950s and the 1970s, a lot of work was done on magnetohydrodynamic recovery systems and related technologies. The Soviet AJAX vehicle design was leaked in the mid-1990s, which sparked the field's recent rebirth. This resulted in an incredible global collaboration for over two decades. Plasma-based flow control appears highly viable, especially for low-power local flow control applications. Low-profile devices that use plasma technology can actuate over brief periods. A particularly promising field is plasma-enhanced combustion, which applies to low and high-speed regimes [62,63,64]. Polymer and composite materials, commonly utilized in the aerospace industry, benefit from plasma treatment for cleaning and adhesive bonding of different materials [65].

e) **Food Industry:** The shelf life of food commodities can be increased via plasma therapy. Recent advances in cold plasma technology have demonstrated remarkable superiority in the deactivation of enzymes and toxins, and spore inactivation [66]. In agriculture and food processing, cutting-edge non-thermal technology using cold plasma has set a standard for quality and safety. It impacts a wide range of physiological processes, including food allergens, polyphenols, packaging, enzyme denaturation, pesticide decomposition, and microbiological decontamination [67].

The food industry has several possible uses for cold plasma, making it an extraordinarily innovative and promising technology. Cold plasma (CP) processing is a sustainable and ecologically friendly way of inactivating the targeted microorganisms without dramatically increasing processing temperatures [68,69]. This non-thermal food processing technique uses ions, radicals, and electrons produced at room temperature to inactivate enzymes and microorganisms [70]. This versatile non-thermal technique is receiving much attention, especially in surface modification and packing materials. This technology is essential for reducing biological risks during post-harvest, processing, and storage, in addition to maintaining the quality of fresh fruits and vegetables [71]. Raw foods may contain human-pathogenic germs that are transmitted through food, like lettuce. These illnesses can, in the worst situation, result in death. Non-thermal plasma, which provides an incredibly effective decrease of living microbial biomass, is one cutting-edge sanitation technique that helps reduce disease and industrial losses [72]. Cold plasma (CP)-mediated priming has the potential to be a novel seed priming technique in place of artificial chemical treatments. Although CP priming is safe, affordable, and environmentally friendly, it has been used less than other seed priming techniques. CP technology can be used for seed priming to improve germination, seed quality, and crop yield in an environmentally friendly way [73]. Also, there is a technique called plasma bubbling, which is used to oxidize protein structure and lower allergenicity in food (for example, sesame milk) [74]. To address the diverse needs of the food industries for various applications, cold plasma's role in food biomolecule modification has grown due to its expanding applicability [75].

f) **Textile Industry:** Plasma has become a game-changer in the textile industry, offering a clean and efficient way to modify fabric properties, which improves qualities like stain resistance, dye absorption, and adhesion of the coatings of the textiles [76]. Unlike traditional wet finishing processes that use harsh chemicals and generate wastewater, plasma treatment is a dry process that significantly reduces water consumption, chemical usage, and environmental impact. Even more innovative textile industry applications may be anticipated as plasma technology develops further, creating high-performance, eco-friendly fabrics for diverse applications.

The modern environmental finishing techniques that the textile industry is seeking to improve fabric quality include plasma treatment as atmospheric-pressure dielectric barrier discharge (APDBD) and corona discharge at atmospheric pressure (CDAP). Both techniques are gaining popularity in the textile industry because they provide numerous benefits over conventional wet processing methods. Following plasma therapy, useful surface groups are introduced by plasma to provide qualities like antibacterial, UV, flame retardant, and antistatic that are employed in cotton, linen, polyester, and surface fabrics. Most fabrics are processed with low-temperature plasma (LTP) to enhance their flame-retardant, antibacterial, UV protection, and antistatic characteristics [77]. Natural dyes are created by plasma irradiation to enhance textile printing performance [78]. Various plasma-based technologies are used to modify the polyester fabric's surface at low temperatures to increase printability [78]. Specifically, atmospheric non-thermal plasmas are appropriate in this case, as most textile materials are polymers with heat sensitivity, making them useful in continuous processes. With the rise in activity and importance of plasma technology among the various material surface modifications available to the textile industry, this field of study has experienced incredible expansion over the past few years [79].

g) **Nanotexture fabrication:** The process of plasma-induced polymer nanotexturing is a highly intriguing way to alter the water-absorbing properties of polymers and produce super-hydrophilic, hydrophobic surfaces [80]. The process that produces a submicrometric texture on a material's surface with a single plasma etching process is known as plasma nano-texturing. The benefits of low environmental effects and high-speed processing can be achieved via plasma nano-texturing [81].

Important surface characteristics like wettability and anti-reflectivity can be controlled using polymer nanotexturing. Interestingly, a one-step procedure based on dry plasma etching uses plasma to produce the appropriate nanofeature characteristics [81]. Numerous processes, including plasma processing, replication from silicon molds, and ultra-short, pulsed laser irradiation, can be used to generate random nanostructuring of polymeric surfaces with pillar-like micro-nanostructures, also referred to as nanotexturing. Specifically, plasma nanotexturing produces nanoscale surface roughness (nanotexture), alters the chemistry and topography of the polymeric surface without changing bulk properties, and can be used to influence optical, wetting, and flow properties as well as biomolecule adsorption [82]. A few appropriate methods for examining the mechanical and wear behaviour of plasma etched/nanotextured polymers and advancing their potential use in a range of applications are nanoindentation and nano-scratch testing [82]. A nano-replica method can create nanotextured surfaces on polymer sheets with high water-repellent properties. First, an organosilicon compound is used as a raw material to build ultra-water-repellent silica thin films onto Si substrates via microwave plasma-enhanced chemical vapor deposition (MPECVD). The nanotextures on the film surface are altered by varying the deposition pressure. Second, electroforming duplicates the films' surface nanotextures on Ni molds. Third, spin coating is used to coat the Ni molds with polystyrene (PS), and nanotextured PS replicas are created due to this technique [83].

h) **Laser Induced Breakdown Spectroscopy (LIBS):** The LIBS technique is a member of the atomic emission spectroscopy technology family [84]. It is an analytical technique through which detection, identification, and characterization of the chemical composition of materials can be done [85]. LIBS is simply accomplished by directing a very powerful laser pulse, most commonly Nd-YAG laser, performed on a volume of solid or liquid or gas or cloud of aerosolized particles at wavelength 1064 nm [84,85,86]. Microplasma, which is generated from the main sample volume, consists of stimulated molecules and atoms along with ablated particles. These excited-state organisms produce light with distinct wavelengths. This light can then be captured using a spectrometer and analyzed on a computer [87,88]. Because each element has a distinct emission spectrum, LIBS can detect all elements. The two types of plasma emission that are produced during a LIBS event are broad and intense continuum radiation known as bremsstrahlung emission and recombination emission, respectively [89,90]. Bremsstrahlung radiations are continuum and intense in nature, and recombination emissions are discrete in nature. At certain wavelengths that are indicative of the chemical components found in the volume, the excited species release radiation. Both the temporal and spectral resolution of the bremsstrahlung emission and recombination emission components of the plasma emission are possible due to their drastically differing rates of decay [86].

The promise of LIBS as a surface characterization technique has been proven over the past few decades. A single apparatus in the air at atmospheric pressure can measure and analyse spots and areas, scan lines, and map compositions. In contrast to other analysis methods performed at surfaces, LIBS has the benefits of surface sensitivity, rather excellent lateral and diagnosis of resolution, and sampling flexibility concerning the size and form of the studied specimen. It has also developed into a useful analysis tool for cultural heritage [91]. The primary characteristics that offer LIBS a very appealing approach for the delineation and conservation of archaeological specimens, artistic work, etc., are the lack of sample preparation, barely damaging nature, fast analytical response, depth profiling analysis, and the capacity for analysis when needed [87]. Usually, LIBS is carried out in the Earth's ambient atmosphere. Nevertheless, there has been a greater interest in LIBS in various atmospheric conditions, particularly for applications in Mars and Lunar exploration programs to enhance isotope signature resolution in recent years [92].

These applications demonstrate the versatility of plasma technology across various industries, contributing to advancements in manufacturing, healthcare, electronics, and beyond.

2.2 Environmental Applications

Plasma technology is a powerful technique for addressing urgent environmental challenges. This section discusses some environmental applications of plasma technology that significantly impact our planet.

a) **Water Purification:** Water purification is one of the most critical applications of plasma technology in the environmental sector. Plasma-based water treatment systems are highly effective in removing contaminants from water sources [93,94]. Plasma can break down pollutants, pathogens, and organic compounds in water, rendering it safe for consumption. Liquid water and plasma react to produce a variety of reactive compounds that destroy and eventually mineralize pollutants in solution [95]. Operating water treatment technologies based on plasma does not require the use of chemicals, which have several advantages over traditional chemical-based systems such as filtration, sedimentation, ozonation, and chlorine used for disinfection [96].

   In the realm of wastewater treatment, non-thermal plasma technology is frequently used to address certain problems related to the major destruction of various aqueous contaminants and water-borne harmful microorganisms, including viruses. Additionally, research has shown that this new method is efficient in deactivating the coronavirus, also known as SARS-CoV-2, which acts as a vector for the deadly virus's propagation in wastewater [97]. Non-thermal plasma can be used to remove emerging pollutants and chemical degradation and remove chemical substances. Plasma can be regarded as a route for direct water desalination and crystallization [98]. Many advanced oxidation processes (AOP) and techniques involve chemical reactions, primarily using the OH radical to mineralize organic compounds in aqueous solutions. AOPs have been suggested as the future wastewater treatment solution due to their capacity to drastically decrease concentration levels of organic pollutants through mineralization [99].

b) **Air Quality Improvement:** The use of plasma technology can significantly enhance air quality. Plasma reactors treat industrial emissions, removing harmful gases, volatile organic compounds (VOCs), and particulate matter [100]. Plasma-based technology helps minimize air pollution's negative impact on human health and the environment by transforming these pollutants into less hazardous compounds or collecting them for proper disposal [101]. Using low-pressure plasma technology, the aerosol and micro dust, sulfide oxide and nitrous oxide, hydrogen sulfide, ammonia, and carbon dioxide can be effectively removed [102].

Meanwhile, research into using atmospheric non-thermal plasma (NTP) generated at ambient temperatures for indoor air purification has increased in recent years, with the benefits of high VOC removal efficiency, high energy economy, and no secondary pollution. The purification process is done mainly by mixing the VOC-contaminated air with a high-ionization NTP containing energetic electrons and active particles, which cause multiple inelastic collisions with the VOC molecules, resulting in degradation and eventually conversion to CO_2 and H_2O. The generation of NTP involves the oxidation and ionization of air molecules (O_2, N_2, and H_2O) via high voltage-generated energetic electrons to produce reactive radicals such as OH, HO_2, O, N, and H, as well as other active particles like as O_3 and H_2O_2. They have enough energy to target organic compounds. Nevertheless, low mineralization efficiency, the production of some unwanted by-products as ozone (O_3), and low energy efficiency in specific NTP types are some of the difficulties this new technology faces. To control indoor air VOC pollution, dielectric barrier discharge (DBD) is an effective source of atmospheric NTP with relatively cheap plasma, in addition to its reputation for effectively eliminating low concentrations of VOCs and odorous compounds. DBD also saves energy and doesn't produce dioxin [103]. Compared to previous plasma-based techniques, plasma catalyst technologies have demonstrated the potential for more thorough VOC oxidation with the least hazardous by-product production and lower energy usage. Therefore, further study must be done before this technology is used indoors [104].

c) **Waste Management:** Plasma provides innovative waste management and disposal solutions. The process for managing plasma waste is called plasma gasification [105]. By employing Plasma ARC Gasification (PAG), organic waste, such as solid waste from municipalities or farms, can be converted into synthetic gas (syngas) [106,107]. Here, the gasification reactions are assisted by thermal plasma while concurrently lowering the concentration of tar in syngas, a gasification by-product [108,109]. This valuable energy source reduces the volume of waste sent to landfills and utilizes waste materials to promote sustainability.

Almost any kind of solid urban garbage, including waste from homes and businesses, may be processed using a plasma torch to produce electricity [110]. The most well-known methods for treating plasma waste are:

- the vitrification of inorganic materials,
- the compaction of organic compounds using plasma and
- the pyrolysis of organic molecules using plasma.

Economic concerns often lead to the usage of multiple waste treatment systems. Most wastes require multiple treatment technologies due to cost reasons. Plasmas are beneficial when a desirable co-product offsets the negative value of waste and treatment costs. Examples of co-products include syngas, hydrogen, and electricity [105]. Plasma gasification burns down char, dioxins, and tars at extreme temperatures, resulting in cleaner syngas with 84% efficiency compared to conventional processes [111].

d) **Renewable Energy:** Plasma technology is a completely revolutionary and creative way to produce renewable energy. Compared to more conventional energy sources like coal or natural gas, its emissions profile is significantly cleaner, which reduces environmental effects while promoting longer-term sustainability. Energy cannot currently be produced via nuclear fusion technology because the energy needed to produce it is more than the energy that can be generated from it. On the other hand, if the reaction is kept going for a few hours, the energy produced will be enough to cover the energy requirement of around 1015 Wh. Tokamak construction is also exceedingly expensive, raising doubts about the project's financial viability. These challenges appear to have been addressed, and thermonuclear fusion will soon prove to be a highly profitable technology due to advancements in technology as well as the increasing need for clean energy [112]. In fusion research, high-temperature plasma confinement is essential to replicate the energy generation process of stars [113].

Nuclear fusion is quickly becoming a viable energy source soon due to its potential for producing zero-carbon power generation without producing high-level waste, which is especially important given the increasing need for energy and rising demands for carbon neutrality. The National Ignition Facility recently conducted a nuclear fusion experiment using 192 lasers, which successfully created more energy than was injected, proving that net energy generation is feasible [114,115]. Moreover, by using microwave plasma technology to generate syngas and applying it as a sustainable energy source, global emissions of CO_2 can be reduced [116]. The next generation's reliance on a cleaner future makes gasification systems essential. An active way to deal with carbon dioxide dissociation is using plasma-based carbon dioxide modification technology, especially when combined with microwave technology.

e) **Textile and Industrial Applications:** Plasma treatments are employed in industries like textiles and manufacturing to reduce water and chemical usage, enhancing sustainability. In contrast to traditional wet treatments used in textile processing, which penetrate the fibers deeply, plasma reacts only with the fabric's surface, leaving the fibers' interior structure unaffected [117]. Surface modification of materials through plasma can improve their durability and functionality, extending product lifecycles and reducing environmental impacts. Plasma technology in material processing reduces the need for perilous items to avoid the release of dangerous greenhouse gases [118,119].

f) **Soil Remediation:** Organic compound-contaminated soil has become a serious environmental problem due to the quick rise of industry and urbanization. Remedial of organic-contaminated soil has gained international recognition [120]. Nowadays, many AOPs are being used for soil remediation, and discharge plasma technology is one of them. In soil remediation, discharge plasma technology is quite beneficial because it is fast, efficient, and does not produce any additional contaminants. It may effectively degrade organic contaminants and prevent secondary contamination from wastewater and waste residue [120]. Rejuvenating land for residential or agricultural use encourages sustainable land management [121].

   In agriculture, organochlorine insecticides are commonly employed to manage pests effectively. However, organochlorine insecticides, such as dichloro-diphenyl-trichloroethane (DDT), pollute groundwater and soil, have carcinogenic effects, and affect mammal and avian reproduction [122]. DDT has an extended half-life of around 36 years, meaning its residues are present for a long time in the soil [123]. Scanning electron microscopy (SEM) [124], an optical microscope, an image camera, energy dispersive X-ray spectroscopy (EDX), and gas chromatography-mass spectrometry (GC-MS) were used to study parameters of the contaminated soil both before and after the treatment with thermal plasma. A SEM study showed that the soil's structure changed as a result of the contaminated soil's contact with thermal air plasma or water vapor plasma. According to the EDX analysis, all chlorine was eliminated from the soil after it had been cleaned with plasmas. According to GC-MS studies, soil cleaning with thermal plasmas also dramatically reduced the levels of organochlorine pesticides in the soil [125].

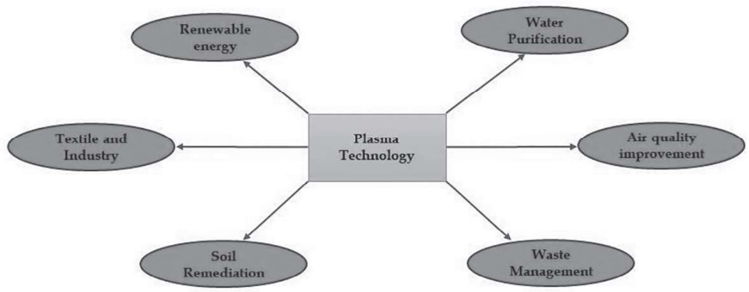

Figure 3: Plasma technology's role in environmental application.

Figure 3 highlights plasma technology's application in the environmental domain that aligns with sustainability principles and responsible resource management, promising an eco-friendlier future.

2.2.1 Recent Agricultural Developments due to Plasma Technology

Plasma agriculture has arisen in recent years as a promising and new field capable of evaluating traditional farming techniques. The use of plasma-based technology in agriculture opens up new options to address a variety of industry concerns, including food security, environmental sustainability, and the demand for increased crop yields. Plasma can be generated using various methods. Each method has unique advantages and may be modified to meet specific agricultural requirements. Furthermore, plasma-activated water (PAW) has emerged as a promising technology for agricultural applications. PAW is created by exposing water to discharges, which produces a variety of active species, including reactive oxygen species (ROS) and reactive nitrogen species (RNS), which increases seed germination rate. The synergistic impact of cold plasma can replace traditional seed germination enhancers and disinfection solutions. Plant growth promotion is one of plasma agriculture's primary focus areas. Plasma and PAW treatments are used to improve seed germination, root development, and crop yield [126,127,128,129]. Cold plasma (CP) technology, as an alternative, can be used to enhance agricultural yields. In recent decades, cold plasma (low-pressure) technology has successfully improved crop germination and growth. The long-term viability of these plasma-treated seeds is of great importance due to the necessity to store and disperse them in many places [130]. By breaking down different mycotoxins, cold plasma technology is another useful method for detoxifying low-moisture foods infected with mycotoxins [131]. Numerous research has demonstrated how using low-temperature plasmas enhances different phases of pre and post-harvest [132]. Examples include seed conditioning in the pre-planting stage, the plant growth stage through the use of PAW as irrigation to enhance growth, the post-harvest stage through the provision of an efficient substitute for managing different pathogens, and the non-food production stage through the provision of an efficient substitute for the surface treatment of natural fibers [133]. Recently, cellular methods such as gene expression analysis, transcriptome profiling, protein expression analysis, and epigenetics have been employed to investigate the molecular mechanisms behind the impacts of plasma on seed germination and plant growth [134].

3. Challenges

Plasma technology, with its wide-ranging applications, faces several challenges. Processing materials and fusion energy rely on regulating and preserving stable plasmas, particularly at high temperatures. Managing materials exposed to extreme plasma conditions and addressing safety concerns are ongoing challenges. Additionally, environmental impacts and regulatory approvals must be addressed in various applications.

As research progresses, many difficulties should be solved in the near future. Understanding plasma, its application, and its challenges requires a deep understanding of various subjects. These disciplines include particle and radiation physics, electronics, and electromagnetic wave theory. Plasma technology has the ability to fundamentally change our understanding of the creation of the universe and its workings. Thermonuclear fusion reactions have also led to advancements in propulsion devices suitable for interplanetary travel, amplifiers and electrical generators without moving parts, reliable communication with spacecraft and re-entry vehicles, and an endless supply of electrical power [94].

4. Upcoming Prospects

In the near future, gaining a better knowledge of plasma dynamics must be prioritized with the associated phenomena. Thus, basic research carried out under controlled conditions has the best potential of yielding significant advancements. This area of research is expected to gain more significance and scope in the future. Plasma has impacted every aspect of life. Plasma is widely used in medicine, energy, environmental sciences, and physics. Plasma's engineering, medical, and environmental applications have been discussed**.** Additional applications include the production of ozone, separation of isotope, plasma particle accelerator, spacecraft ion propulsion, spray coating using plasma, corona dying of ink and textiles, water purification by ozone formation, and more. While present difficulties may seem intimidating, the advantages of resolving them address the investment in plasma technology. As these applications expand, plasma physics will become increasingly essential and find many new real-world applications. Advances in plasma applications will highlight the importance of plasma physics and engineering.

5. Conclusion

In conclusion, the properties and wide range of applications of plasma technology in various fields like material processing, healthcare and medicine, nanotexture fabrication, aerospace, food, and textile industries are discussed in this review. Along with these applications, plasma technology's environmental and agricultural use is also reviewed, which helps humanity maintain a green and eco-friendly environment. Plasma technology is being tested in clinical trials for applications in domains like cancer treatment. Additionally, it has also been used in the cosmetic industry. Plasma technology has gained interest recently due to its widespread application [135, 136,137]. Research into plasma acceleration processes is still ongoing. In the early stages, particle acceleration has been successfully studied for laser accelerators and current driving schemes.

Further investigation is necessary as particle acceleration in very turbulent plasmas is still in its early stages. In the fields of space plasma and astrophysics, this research is crucial. Much more research is needed on particle acceleration in highly turbulent plasmas, as the field is still relatively new [138]. The plasma scientist community is confident that further exciting breakthroughs will continue to stimulate innovations and discoveries in the near future, provided research and education are adequately funded and supported by public bodies as well as private investors [139].

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