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Review of the cold atmospheric plasma technology application in food, disinfection, and textiles: A way forward for achieving circular economy

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Cold atmospheric plasma (CAP) is a promising technology quite useful in many industries including biotechnology, biomedical, textiles, and food processing. The contrivance of plasma technology can be a potential game-changer to use in any possible way in these industries. This CAP technology is technically a green process with no generation of chemically harmful substances with more ecological and economic benefits. This review article will focus on the research done in the textile industry and food processing, how plasma brings in an effective change in these industrial sectors as well the as application of CAP in disinfection, sterilization, microbial inactivation, and surface modification to obtain desirable results. Recently, there have been reports of successful use of CAP technology for surface inactivation of SARS-CoV-2, plasma-activated water for disinfection of SARS-CoV-2. This article will streamline the innovations in textiles and food industries achieved using plasma technology and what gaps industries face while manufacturing. The focus will be on what research has already done while depicting the gaps and opportunities for using plasma technology in these industries and making use of it to achieve a circular economy, which is one of the major policies of the European countries. A circular economy enables manufactures to produce goods which can be reused, recycled, refurbished, and repaired rather than scrapping them after a single use. The reduction of harmful chemicals, wastewater treatment, and sterilization is achieved using plasma technology and allows reusing the resources which consequently helps to achieve most of the UN's sustainable development goals and help society to live a sustainable and better life.

KEYWORDS

cold atmosphere plasma, circular economy, food industry, disinfection, textile—clothing industry

Introduction

Plasma, as regarded by all, is the fourth state of matter. It is a partially ionized gas comprising of electrons, ions, and neutral particles. Irving Langmuir first used the term plasma to this ionized gas in 1927 [1]. More than 99% of the matter of the visible universe is said to be in the plasma state. Plasma can be produced in laboratories by different techniques and predominantly by supplying electrical energy to a gas. When the voltage applied between two electrodes is high enough to cause a breakdown of the gas, a plasma is formed. Due to the very high mobility of the electrons, they can rapidly gain energy from the applied electric field and transfer their energy to the neutral particles through collisions. Once an electron hits another atom with sufficient energy, it can rip off another electron from an atom and thus will create a cascading effect, ending up with many electrons and ions, and a plasma is created. When the excited particles relax to low energy states, we see the plasma glow. Plasma breakdown voltage between the electrodes for a specific gas depends on the pressure and the distance between the electrodes, according to Paschen's Law [2, 3] and with this breakdown voltage, electrons are generated that later contribute to electron avalanches and secondary electron emission processes [4]. Figure 1 shows the breakdown voltage for various gases as a function of the product of pressure and distance between the electrodes. As long as the applied voltage exceeds the breakdown voltage, which varies for different gases, plasma will continue to flow. Additionally, when this breakdown voltage is reached, gases lose their insulating properties and become conductors [5]. In gas plasma, breakdown voltage depends on pressure and electrode distance. Therefore, the breakdown voltage is high, when the product of pressure and electrode distance is low since few collisions will occur and the breakdown voltage is low when the product of pressure and electrode distance is high because of occurring many collisions [5]. Different gases have similar patterns of pressure and distance between electrodes, which yields a minimum product value between 130 and 1,300 Pa cm [6].

An electric field is applied to a neutral gas in order to create and maintain low-temperature plasmas in industrial and scientific settings [7].

The plasma can be classified on the ground of relative temperatures of electrons, ions, and neutrals. There are two main categories in which plasma can be classified—"thermal plasma" and "nonthermal plasma". Thermal plasmas have electrons and heavy particles at the same temperature i.e., they are at thermal equilibrium. On the other hand, non-thermal plasmas have very high electron temperature, whereas the heavy particles i.e., ions and neutrals remain at a much lower temperature (sometimes room temperature). CAP is referred to as nonthermal plasma because electrons remain at a very high temperature than the heavy particles that are near room temperature [8]. In thermal plasma delivery, high pressures, beyond 10^5 Pa, require a power of around 50 MW, whereas

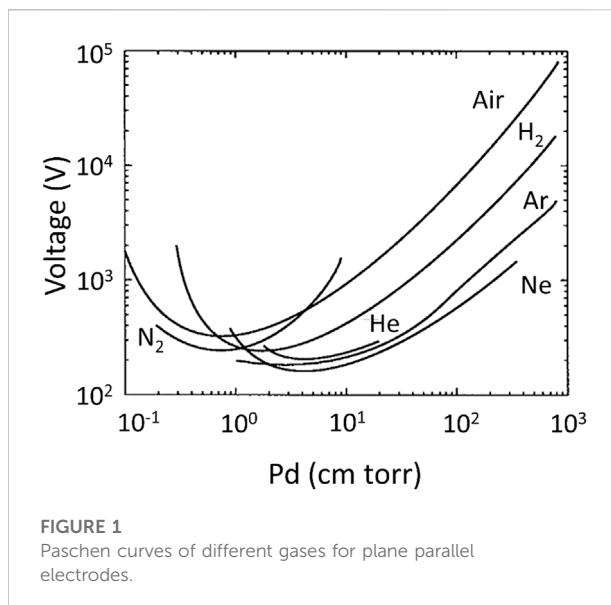


FIGURE 1
Paschen curves of different gases for plane parallel electrodes.

cold plasma does not require high power for a generation [9]. The various methods to produce CAP in the lab include dielectric barrier discharge - DBD method, the Plasma Jet method, and the Corona discharge [10, 11]. Several different gases such as Argon, Helium, Air, and Nitrogen can be used to produce CAP. Various high voltage electrical excitation sources such as KHz frequency AC, DC, pulse DC, radio frequency (RF), and microwave (MW) sources are used to excite the plasma. Since the discharge occurs under atmospheric conditions, air can diffuse into the discharge regions and as a result, various reactive oxygen species (ROS) and reactive nitrogen species (RNS) such as O_3 , HO^\bullet , O_2^- , NO, N_2O , NO_2 is formed in the plasma phase. Also, these reactive species are formed by plasma-liquid interaction or by plasma-air interaction outside the discharge zone. These reactive species are biologically very important. Here, we will focus on the two most widely used techniques -DBD and Plasma Jet discharge in this review and we will highlight the recent advancements in plasma-activated water (PAW).

Dielectric Barrier Discharge-DBD Method: The plasma creation with the DBD method is gaining significance due to its economic benefits at the present time. It is probably one of the most valuable types of plasma technology because of its simple arrangements and adaptability for the electrodes shape and the dielectric material used [12]. DBD plasma is caused by the application of a high voltage in between two metal electrodes (high voltage terminal and ground electrode) as shown in Figure 2. One or both electrodes are surrounded by a dielectric material such as glass, quartz, polymer, mica, or artistic material [13]. Gaps in between them vary from 0.1 mm to a few centimeters and electron density in the argon plasma is in the order of 10^{14} cm^{-3} [14]. Gas pressures between 10^4 and 10^6 Pa are the normal range used in DBD activity,

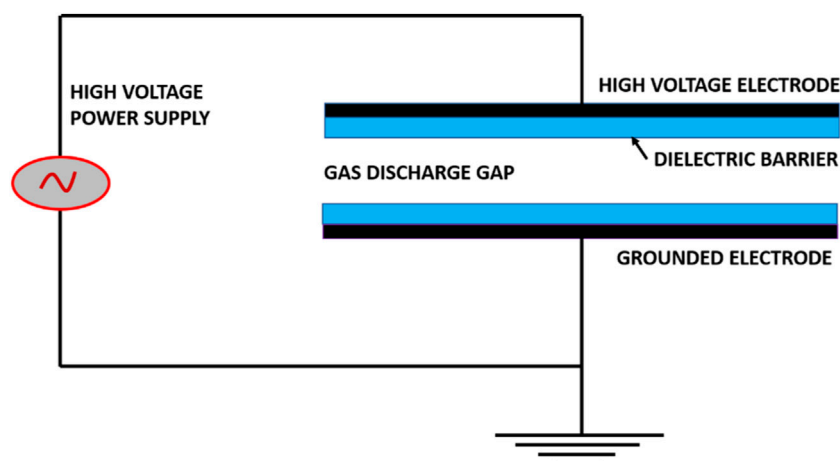


FIGURE 2
Schematic of dielectric barrier discharge—DBD.

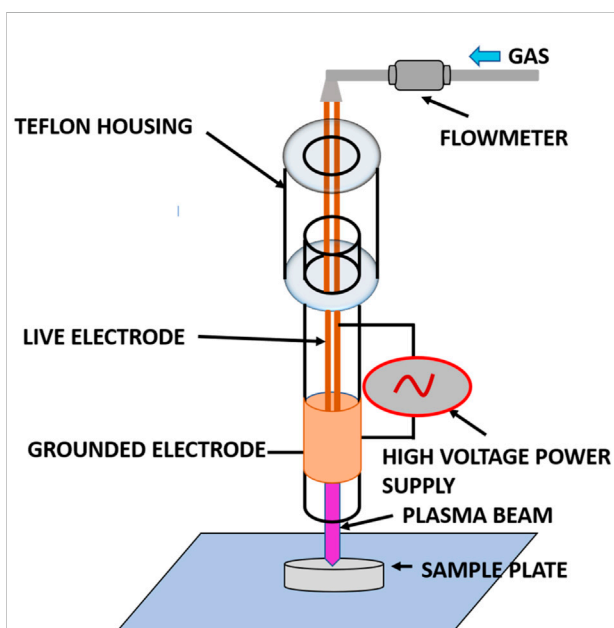


FIGURE 3
Laboratory set up of Cold plasma (CAP) at atmospheric pressure.

a live electrode as shown in Figure 3. When power is applied to form a discharge, it ignites and operates on a feed gas that passes between an outer grounded electrode and a live electrode, consequently, a beam of discharge will be produced [5]. In this arrangement, free electrons are accelerated, which collide with molecules of gas to form reactive species. A high flow rate of gas is established between electrodes and the plasma formed between the electrode comes out into the open air with the gas flow. Plasma jets produce a constant, steady, and unvarying release of plasma at atmospheric pressure [5]. A collection of various cold plasma jet setups has been discussed in detail by Lu et al. [17]. Typical values of plasma parameters such as electron density and temperature of CAP plasma devices vary in the 10^{13} – 10^{15} cm^{-3} and 1–10 eV ranges respectively [18–22]. Due to its simplistic model and production of cold plasma, it is highly used in the biomedical field, for example, KINPen, a CAP jet-based EU-certified medical device can reduce microbial burden significantly compared to the existing methods. KINPen uses Argon as feed gas to treat chronic wounds for patients [23].

Plasma Activated Water—PAW: The reactive species present in the plasma can be effectively used to produce PAW. The common sources to generate PAW are CAP-DBD and plasma jet. When CAP-DBD and plasma jet directly treated aqueous solutions like tap water, phosphate buffer saline, sodium chloride, and N-Acetylcysteine, then the aqueous solution is pronounced as plasma activated liquid (PAL) as shown in Figure 3. When only water is treated with plasma discharge sources pronounced as plasma-activated water (PAW) [24]. The various ROS and RNS produced in the plasma phase as well as during plasma-liquid interaction diffuse into the liquid sample during plasma treatment. Therefore, PAW also contains these reactive species, as CAP-DBD and plasma jet produce [24, 25]. Zhou et al. have demonstrated briefly the different mechanisms

followed by recurrence bands fluctuating between 10 and 50 MHz and voltage adequacy fluctuating between 1 and 100 kV_{rms} for alternating current [15].

Plasma Jet discharge: Plasma jets cover a variety of arrangements in which the plasma is generated using different gases [9, 16]. Coaxial electrodes are the most commonly used design, in which gas flows in between the electrodes. In this method, a discharge is produced between a ground electrode and

to generate PAW to make it more effective and the chemistry of the originated reactive species and its relative application in the biomedical field [23].

In this review, we will focus on the applications of the different plasma generating methods in some of the major industries such as food, textile, and disinfection. We will highlight the significance of utilizing plasma in these industries with a clear marking of the shortcomings in the present situation. Finally, the review will emphasize the ways of utilizing plasma in industries to achieve a circular economy as a way forward to contribute to the UN SDG.

CAP for food industry

In a busy life, people are willing to find fresh but long-lasting food. It could be possible by thermal and non-thermal technologies while preserving all the nutrients of the food. Though thermal technologies might reduce the microbes' counts, they also degrade the quality by destroying the heat-sensitive vitamins and micronutrients [4]. Alternatively, irradiation, low-temperature plasma technique, pulsed electric field, high hydrostatic pressure, pulsed UV-light, and ultrasound processing are some non-thermal techniques for the inactivation or reduction of the microbial load on various food items. However, many issues exist with the non-thermal techniques such as in the case of microbial inactivation, irradiation can cause food poisoning, pulsed UV light has low penetrating power, pulsed electric field has a high initial cost with less effect on spores and enzymes, ultrasound can cause changes in the quality as well as physio-chemical properties of the food, high hydrostatic pressure denatures proteins and causes unfolding [26]. One of the non-thermal technologies is CAP in which high temperature is not required for microbial inactivation and ultimately preserves or has a minor effect on the color, smell, taste, and nutritional value of food [5]. CAP produced by the DBD method is an imminent technology to inactivate pathogens effectively in both cases under suitable conditions. Parameters that can affect the efficacy of CAP-DBD treatment in food processing could be factors involved in the operation-voltage, current, type of gas, relative humidity, temperature, flow rate, frequency, material, thickness, and spacing of electrodes and barrier, treatment, and storage time, headspace and volume ratio product in-package and product rolling, direct and remote exposure, hurdle treatment (synergism of different technologies); product features- surface characteristics, product type (plant or animal-based) and composition, and water content; microbiological factors- initial count, type of pathogen, growth rate [15].

The reduction of *S. Typhimurium* and *L. monocytogenes* microbes with CAP is more effective on the solid surface rather than in a liquid carrier because CAP reactive species need to diffuse within the liquid medium as the highly

reactive species are not able to penetrate far into the liquid medium. However, the study by Smet et al. correspondingly shows that the food structure essentially impacts the inactivation conduct and viability of CAP [28]. The main components to inactivate the microbes in CAP are the reactive species-ROS and RNS. These reactive species attack the cell wall of the pathogens and intracellular components, making them rupture along with peptidoglycan or lipopolysaccharides oxidation [29]. Nevertheless, reactive species have been directly associated with the oxidative stress on the exterior surface of microbial cells where the cell membrane ruptures by peroxidation of lipids, inactivation of enzymes, denaturation of protein, and DNA cleavage [29]. Microbiologists use log reduction to express the relative number of living microbes that are eliminated by disinfection. Artificially injected *Salmonella spp.*, *Listeria monocytogenes*, and *E. coli* strain O157:H7 on apples, cantaloupe, and iceberg lettuce reduces the strain by at least units by treating with atmospheric uniform glow discharge plasma [30]. If treated indirectly with gliding arc plasma, *E. coli* O157:H7 shows a reduction by 3 log units within 3 min of treatment [31]. In strawberries, the application of non-thermal cold plasma results in the minimal degradation of two main components: anthocyanin and ascorbic acid at 80 kV [32].

Cold plasma with the appropriate reactive species has been successfully used in meat industries to inactivate some undesirable bacteria including *E. coli*, *Listeria monocytogenes*, and *salmonella spp* [25]. Gorbanev et al. have applied cold atmospheric plasma to produce ready-to-use meat bresaola and achieved with the reduction of redness by 40–70% and bacteria *L. innocua* by up to $1.6 \pm 0.5 \log_{10}$ cfu/g (at 15.5–62 W for 2–60 s) [26]. Indirect plasma was also used for microbial inactivation in pork and achieved to hold bacteria for up to 20 days at 5°C; however, effects on other parameters like color and pH, were observed greater in more exposure time.

Fresh fruits and vegetables are prone to browning due to the chemical reaction that results in food wastage. The more fruits and vegetables get brown, the fewer vitamins they have. CAP successfully reduced the activity of two responsible enzymes—*polyphenol oxidase* and *peroxidase* for the browning effect on the freshly cut vegetables and fruits by approximately 90% (180 s treatment) and 85% (240 s) using, respectively as well as pH remains below the room temperature during plasma treatment [10]. A roller conveyor plasma device composed of rolling electrodes encompasses a plastic rod enveloped with silicon and aluminum sheet placed in between the high voltage electrode and the ground electrode and this device successfully inactivated the *Xanthomonas campestris* on a cabbage leaf [33]. Some agricultural products release ethylene gas, which reduces the freshness of the products. The plasma DBD has been used to decompose the ethylene gas by diluting it with a gas mixture of oxygen, nitrogen, and carbon dioxide, which can be further used in transportation containers. However,

TABLE 1 Application of cold atmospheric plasma on eatables and the respective results.

S.No.	Source	Acted on	Results	References
1	CAP-DBD Potential difference (PD)- 15 kV Freq- 12.7 kHz (Air)	Apple	- Reduction in browning effect - Changes in the respiratory pathways of the cells - pH remains constant	[10]
2	CAP-DBD PD- 15 kV	Pear	- Yeast/molds Microbial reduction by 2.5 log CFU/fruit - Remarkable changes in the peel color and antioxidant capacity	[48]
3	CAP-DBD PD- 30, 40, 50 kV (Air)	Tomato	- Decrease in Peroxidase activity	[49]
4	CAP-DBD PD-60Kv Freq-50 kHz	Strawberry	- Reduction in aerobic mesophilic bacteria, yeast and mould by 2.5 log ₁₀ within 24 h with 5 min treatment	[50]
5	CAP-DBD (He, He + O ₂) PD-3 kV Freq-30 kHz	Pork loin	- Inactivation of <i>E. coli</i> and <i>L. monocytogenes</i> reduced by 0.26 and 0.50 log cycles at 5 min and by 0.34 and 0.55 log units at 10 min, treatment, respectively - Greater lipid oxidation observed - pH, L values (lightness) significantly reduced - Redness and yellowness show no significant changes - Has potential of inactivation of pathogens - Reduction in sensory quality parameters	[51]
6	CAP-DBD (Air) PD-70 kV	Raw broiler breast meat	- Reduction in the psychrophiles, <i>Campylobacter</i> , <i>Salmonella</i> after 60 s treatments by 0.5, 0.7, 0.4 log respectively - No further of microbial counts after 60 s treatments - No significant change in redness - increase in lightness observed	[52]
7	CAP-DBD (Air) PD-80 kV	Blueberries	- Degradation efficacy of pesticides- boscalid and Imidacloprid by ~80 and ~75% respectively - Increase in phenol and flavonoid contents - Decrease in ascorbic acid	[53]
8	CAP-DBD PD-80 kV	Wheat and barley	- Reduced microbial load by ~2.5 log - In wheat grains hydrophobicity decreased	[54]
9	CAP-DBD Power- 250 W Freq-15 kHz	Cheese	- Pathogens reduction in terms of D- value (the time required to kill 1 log units of the pathogen) • <i>E. coli</i> —2.67 at 60 s • <i>Salmonella Typhimurium</i> —3.10 at 45 s • <i>Listeria monocytogenes</i> —1.65 at 7 min	[55]
10	Atmospheric corona discharge PD - 9 kV AC power supply	Milk	- Approximately 50% reduction of the <i>E. coli</i> at 3 min treatment observed - No significant change in pH and color in the raw milk sample	[56]
11	High voltage atmospheric cold plasma PD—90 kV	Orange juice	- <i>Salmonella Typhimurium</i> microbe reduction by 5 log - In air reduction of vitamin C by 22% observed	[57]
12	CAP (He—5L/min) 6 kV	Chicken skin and muscle	- Inactivation of <i>Listeria innocua</i>	[58]
13	CAP (Ar)	Fish products	- Survival of <i>L.innocua</i> decreased by 0.19–1.04 log cycles	[59]
14	Atmospheric plasma -DBD	Cabbage leaf	- Inactivation of <i>Xanthomonas campestris</i>	[33]

along with this process, the production of harmful gases such as ozone, carbon monoxide, and hydrogen was observed, but the DBD with Ag-Zeolite reduced the concentration of carbon monoxide with O₃ reduction [34]. Ma et al. shows ambient

result regarding enzymatic browning degradation and reduction in polyphenol oxidase activity in apple slices [35]. Surowsky et al. shows a reduction in the activity of polyphenol oxidase and peroxidase [36]. ROS, such as atomic oxygen and

particularly OH radicals, can cleave peptide bonds, oxidize amino acid side chains and form protein–protein cross-linkages. Garofulić et al. demonstrated it is that evident longer exposure time of cold plasma reduce the content of anthocyanin [37]. But short treatment in large volumes causes no degradation as well as plasma-treated on sour cherry marasca juice found the highest content of anthocyanin as compared to untreated and pasteurized juice. Kovačević et al. also show that the content of anthocyanin in pomegranate juice is highest in plasma treated than in untreated one [38]. Botrytis cinerea fungus after mulberry harvest [39] shows CAP treatment at 0, 0.5, 1, 2, 3 min with 0, 2, 3 V on mulberry effectively reduce the growth of botrytis cinerea. CAP effectively shows auspicious results in the inactivation of *S. enterica* and *bacillus* spores on the surface of the black peppercorns and moreover, CAP does not affect the color, pepperine, and oil content [40]. Degradation of *Aspergillus* spp. Spores on hazelnut increased with the applied reference voltage and the frequency [41]. Zahoranová et. al have shown the inhibition of different pathogens, *Aspergillus flavus*, *Alternaria alternata*, and *Fusarium culmorum* non the maize surface by cold atmospheric plasma and also gave surface finishing without the use of any chemicals [42]. CAP also effectively reduced the microbial count in dried herbal tea, which provides industrial relevance to CAP [43]. Table 1 comprehensively highlights the application of cold atmospheric plasma to various foods. Moreover, the inactivation of microbes is also induced by washing food with PAW which can replace the chemical sanitizer. PAW effectively disinfected the rocket salad [44], pesticide removal was observed on grapes dipped in PAW for 10 min [45], able to disinfect many meat products [46], seafood preservation and decontamination is also possible [47]. Hence, along with CAP technology, PAW is so effective to preserve and decontaminate food items.

CAP produces these reactive species at a time and synergizes all these reactive species responsible for the effective inactivation of microbes. The reactivity of these species transfers into physical and chemical processes such as particle collisions, mass transfer and complex chemical processes at the interface, and photolysis by absorbed UV photons.

Many inquiries regarding the types of species produced during plasma exposure and their particular role in the process of inactivation of the microbes actually still need to be considered. Moreover, complete knowledge of the inactivation process helps to make effective tools. In terms of cost CAP's efficiency need to evaluate. The potential of cold plasma technology induces researchers to develop and modify all processes for nutritional, safer, and more beneficial products than conventional technology. Most eatables such as apples and strawberries are overloaded with chemicals/wax for increasing the shelf life which happens in conventional technology. CAP technology can not only sustain the structural and chemical composition of the product but also reduces the chemical release to the environment. Application of CAP to a wide range of food

has been done but still, there is a lack of information regarding the physicochemical, sensorial, and nutritional properties of food. Researchers found that the CAP effect on food is very minimal, quality remains intact such as color, taste and pH. So far, it is showing positive results which increases CAP's potential as an environment-friendly technology. Risk assessment of CAP must be conducted by authorities before it is been commercialized. Additionally, plasma in an aqueous solution generates ROS and RONS which are mainly responsible for the inactivation of pathogens and bacteria. The European Commission has no curtailments regarding the use of plasma technology to preserve organic food [60]. However, plasma also generates nitrates, nitrites, and hydrogen peroxide, which may react and produce toxins compounds such as peroxyxynitrous acid [34]. Hence, studies need to be done that no harmful byproducts are produced by CAP treatment and simultaneously maintain the nutritional and chemical qualities of the food. Ozone, which is one main reactive species is unstable and decomposes to a pure oxygen state and the half-life of ozone molecules varies from a few seconds to hours [61]. The unconsumed oxygen reverts to oxygen with no residuals. Ozone and NO_x are produced in very low concentrations which one can find by quantification of species produced by CAP. Their production can be controlled by properly tuning the plasma reactor. Cold plasma can meet numerous expectations that the food industry requires, provided a complete knowledge of the process of operation is available. However, more studies on the utilization of CAP need to be carried out from a molecular perspective of proteins/enzymes present in both the microbes as well as the food.

CAP for disinfection

Disinfection/Sterilization of different kinds of equipment in the bio-medical field is necessary to avoid unnecessary secondary infections caused due to pathogens. Various techniques are used to sterilize medical equipment, such as the use of ethylene oxide, peracetic acid, hydrogen peroxide, formaldehyde, exposure to UV, treatment with gamma-ray, and autoclaving [4]. Table 2 signifies the different existing processes and the pros and cons of utilizing these techniques.

Plasma has broad benefits in the biomedical field. CAP effectively produces a mixture of various long-lived and short-lived reactive species which works synergistically in the plasma environment that increases its applicability. Plasma is now used prevalently to sterilize medical devices found without any alteration in the devices happen and also produce no chemical residues. However, to minimize the effect of ozone on any object or humans, the CAP device can be customized according to the requirement of the target to be treated. For example, by using an air pump activated charcoal and manganese dioxide pass through the plasma device to block or decrease the concentration of ozone [69]. It can be used to sterilize, and inactivate a large number of

TABLE 2 Existing sterilization process and its advantage and disadvantages.

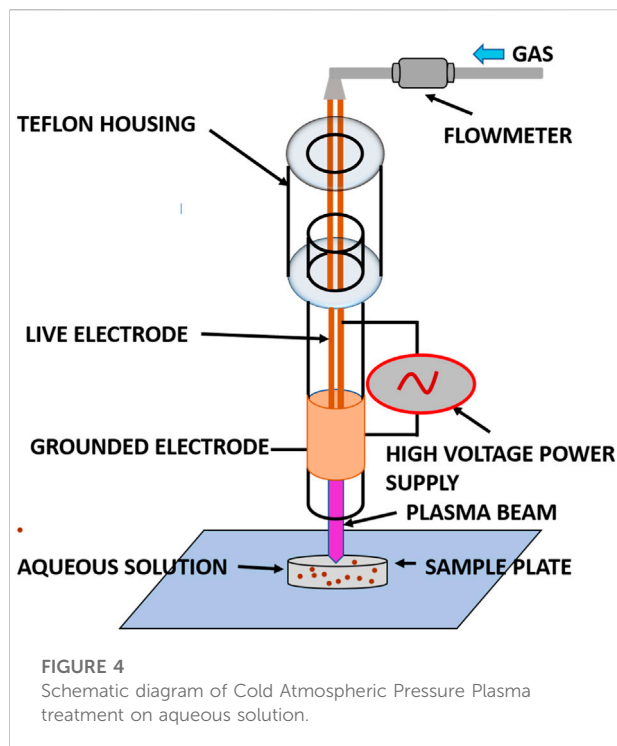
S.No.	Sterilize process	Advantage	Disadvantage	References
1	Autoclave	<ul style="list-style-type: none"> • Quick process • Highly penetrative • Leaves no toxic residues 	<ul style="list-style-type: none"> • Higher temperatures > 100°C could destruct the material 	[62, 63]
2	Gamma rays	<ul style="list-style-type: none"> • Highly penetrative • Low temperature • Leaves no toxic residues 	<ul style="list-style-type: none"> • Slow process • Could change properties of material 	[62]
3	UV treatment	<ul style="list-style-type: none"> • Fast process • Low cost • Involves low temperature • No toxic residues produce 	<ul style="list-style-type: none"> • Could damage the material 	[64, 65]
4	Chemical treatments	<ul style="list-style-type: none"> • Effective • Low temperature 	<ul style="list-style-type: none"> • Toxic Gases involves that may be carcinogenic • Requires separate room 	[66]
5	CAP	<ul style="list-style-type: none"> • Environmentally friendly • No residues produce • Safe and easy to handle • economical 	<ul style="list-style-type: none"> • Low penetrating power 	[67, 68]

pathogens, and has great potential in dentistry and therapeutic also, disinfection of medical devices, beds, surgical masks, gloves, and floors [70, 71]. Hence, in comparison to the various disinfection methods CAP is a promising technology with fewer human interventions.

Recently, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has devastated the livelihood of many people and also led to the loss of human lives. As we are aware, this virus spreads through respiratory droplets from one person to the other and hence disinfection of the areas is highly important. According to the World health organization (WHO), there are some possible modes of transmission of SARS-COV-2 such as airborne transmission, contact and droplet transmission, and fomite transmission [72]. The most common method of disinfection is the use of sodium hypochlorite solution, but the repeated usage of huge quantities of this chemical affects the soil and human/animal health. An alternative to this chemical treatment can be achieved through CAP. Most studies found that SARS-CoV-2 virus surface inactivation is possible using CAP over many surfaces like desks and chairs. The important aspects of surface inactivation are the composition of the material, the roughness of the surface or material, and the absorptivity of the material. For example, treatment of argon-fed cold plasma on the metal surface shows higher discharge intensity at the interface which produced more species which are directly involved in the inactivation process and consequently increases the efficiency. On rough surfaces, however, the inactivation of microbes is low. Also, absorptivity plays a major role in surface inactivation like cardboard protects the SARS-CoV-2 virus from plasma discharge disrupting inactivation efficiency. So, material roughness and absorptivity are major factors which affect the surface

inactivation process in the case of the SARS-CoV-2 virus and material composition is the second-most important factor. Unlike argon-fed plasma, helium-fed plasma was not able to achieve complete disinfection of SARS-COV-2 virus on metals, plastics, and cardboard even at higher treatment time [73]. The reason is Helium plasma a has much lower RONS concentration than Argon for the same working state. Therefore, the RONS concentration is also important in SARS-CoV-2 surface inactivation. No chemical is needed and Plasma is a safer method than alcohol, and UV radiation methods [73]. In addition, PAW also can be used to disinfect medical devices. Ganesh Subramanian et al. also reported the inactivation of *Pseudomonas aeruginosa*, bacteria which is responsible for the infection which originated in hospitals [74].

CAP-DBD can curb airborne transmission by completely inactivating the aerosols containing the virus or purifying SARS-CoV-2 RNA suspension [75]. Cortázar et al. have shown that using CAP and PAW, the SARS-CoV-2 and H1N1 influenza virus inactivation without any damage or alteration of the healthy cells [77]. Alternatively, PAW can also effectively repress the pseudovirus infection through S protein inactivation of the pseudo viruses with SARS-CoV-2 S protein used as a model [78]. The CAP is very helpful in the deactivation of SARS-CoV-2 on food or food packages and in addition, it can increase the shelf life of food [79]. Absolute deactivation of SARS-CoV-2 spike protein and RNA using CAP has been reported [80]. Disinfection of masks used to avoid SARS-CoV-2 virus achieved using hydrogen peroxide plasma [81]. Futuristic development is going on, and the need of the moment is to find the potential of CAP to curb the announced epidemic of SARS-COV-2.



CAP for textile industry

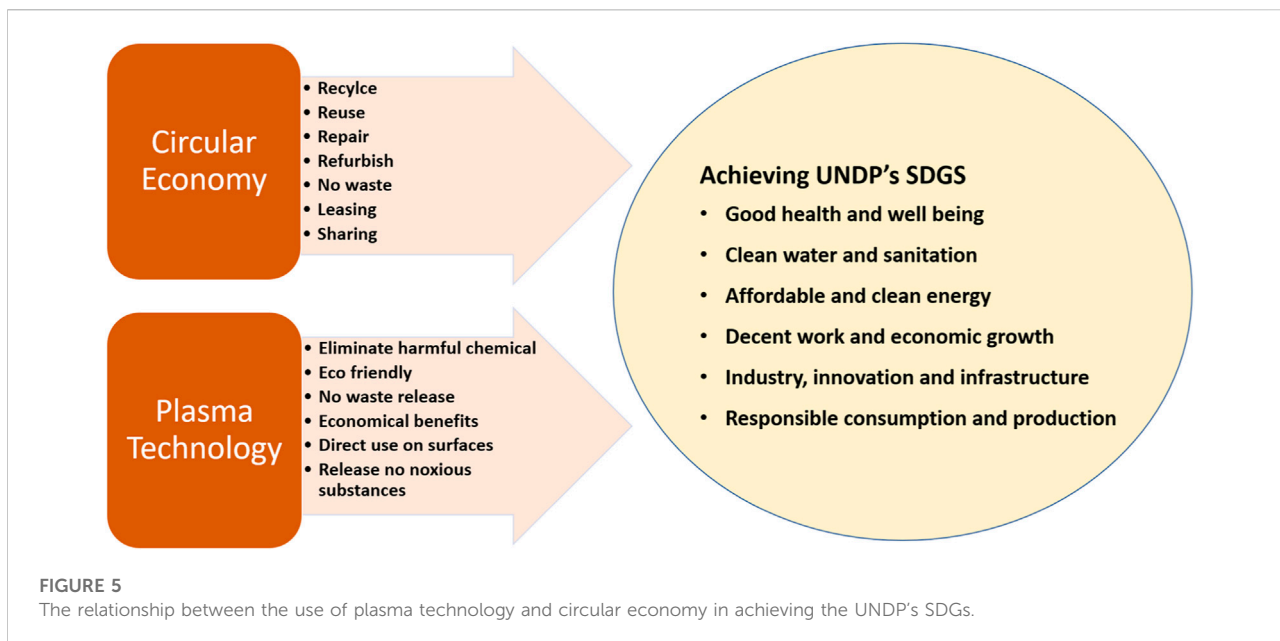
In terms of textiles and apparel, India is among the world's most significant markets. Researchers need to analyze the limitations that this industry is facing, which not only benefits to enhance the potential of the textile industry but also helps in the economic development in India as well as throughout the world. Now, the stimulus of cold plasma technology in textiles gives a new direction to develop new finished products and improve the quality of already existing products which are ultimately beneficial to the industry as well as society also. In the future, the ecological and energy-saving complications demand for a steady substitution of numerous conventional wet science-based material handling which utilizes a lot of water, power, and releases effluents, by different types of low-alcohol and dry-completing cycles. The waste produced by the wet method is usually dumped into rivers and oceans leading to water pollution. Plasma technology also has the potential to reduce the water pollution generated by a wet chemical used in the manufacturing process. It is a completely dry process and does not release any toxins and harmful chemicals.

Plasma technology has many applications for textile advancement and modifying its properties according to the need, such as, it can enhance mechanical properties of textiles, can provide antistatic finishing, can improve surface wettability, can improve dyeing and printing sustainability, can convert normal into flame retardant fabrics, can improve adhesion

[82]. With the increase in fiber production, the efforts to adopt environment-friendly production processes and technologies have been incentivized; for example, REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) initiation in European countries forced industries to tackle the environmental problem by innovation [83]. Plasma can be a game changer by modifying the conventional methods used in textile industries. In textile industries, dye lost in the effluents causes many environmental problems [84]. Here, plasma technology can remove grease or wax in fibers, which occurs in fibers naturally or synthetically. Also, it can facilitate the diffusion of dye molecules into the fiber making the dyeing process easier, and also results in improved intensity of the color and change in the color after washing off the textiles [85, 86]. Plasma technology can also improve dye exhaustion, the mass of the dye absorbed by the textile divided by the total initial mass of dye in the bath. In addition, enhancing dyeing consistency, cutting dye and water consumption, and enabling the reuse of effluents, can also significantly reduce operating costs and impact the environment [87–89]. The changes in the surface modification and chemical configuration of the dyed fabrics upon application of plasma have been studied [90–94]. The particular exposure time, applied voltage, feed gas, etc., contribute to the enhancement of dyeability [95–97]. When textiles are treated with plasma, it undergoes significant physical and chemical changes like changes in layers of the surface, structural, and physical properties. Some effects like plasma cleaning [98], plasma activation [99], plasma-assisted grafting [100], and plasma polymerization are majorly observed [101].

Antimicrobial efficiency of the fabric is usually achieved by a conventional process using salts, detergents and baths can be overcome by using DC sputtering in which no chemicals are used and the process duration is minimal. Antimicrobial efficiency sustains even after 30 cycles of laundry baths [102] for the plasma based sputtering process. Plasma technology is used to modify polypropylene fibers to increase the fixing of the copper particles on the surface of the fabric and enhance disinfection [103]. Using Argon, low-temperature plasma decolorization of denim fabrics can be achieved, with a smoother surface and is less time-consuming than the conventional process [104]. The hygroscopicity and dye adsorption ability of wool samples increased in which oxygen gas was used [105]. The space between warp and weft yarn is occluded when the surface of the fabric is first coated with aluminum and copper and then treated with low-temperature plasma without any alteration in the physical structure of the fabric [106]. The shrink-resistant and anti-felting effects on the wool fabrics were observed using low-temperature plasma [107].

Textile industries produce cotton, wool, and jute, among other materials, to provide customers with quality products at a reasonable price. Hence, they contribute significantly to



economic development regarding output, employment, and foreign exchange. There are many severe problems with the textile industry worldwide concerning production. During the dyeing and printing process, workers are exposed to many toxic chemicals [108–110]. Many serious diseases, such as cancer, breathing, lung infections, and stomach infections, can be caused by the use of formaldehyde-releasing solvents. To make fire-resistant textiles, flame retardants are used [111], but they contain very harsh chemicals that harm not only people but also the environment since they do not decompose easily and become part of the food chain through the soil. Thereafter, the chemical waste produced by this industry is dumped into the rivers, disrupting aquatic life. Many developments have been made, such as replacing harmful chemicals with safer ones, using the same water again and again to avoid water wastage, etc. However, there is a dire need to find safer and cleaner technologies to reduce or diminish such severe issues which can be accomplished by using plasma technology. For example, by using the technique of plasma grafting to the surface of the polymer, the flame retardation properties can be achieved, and additionally, smoke reduction was observed [112], of the nylon fabric treated with atmospheric plasma jet increases surface roughness which enhanced dye intensity [113], thus it can help in reduced intake of dyes with enhanced color properties. Though many research works have shown that plasma technology reduces the use of chemicals in textile processing, a comprehensive evaluation of the various dyes in various water conditions (hard, soft) and pH conditions is essential to figuring out the right choice of technology and color impact on the fabrics.

Circular economy and plasma technology

The circular economy intends to depend on sustainable power, limits, tracks, and removes the utilization of poisonous chemical substances; and eliminate squandering through the cautious plan. Some simple principles effortlessly define the circular economy [114]. Some of the principles include designing waste reduction methods, building resilience through diversity and creating more think in “systems”. The main motto of the circular economy is to create products which are organic and easily eliminated from the waste cycle can help in the high-quality retention. The products should not be in the category of waste and should be able to recycle the products.

Plasma technology can be helpful in the goal of achieving a circular economy. Figure 5 shows the relationship between the plasma technology and circular economy, which achieves UNDP's SDGS goals. Apart from being an eco-friendly technology, it is helpful in the development of manufacturing of many products which replace or reduce the inclusion of harmful chemical products. For example, in all the above-mentioned industries such as food, disinfection and textiles we can achieve circular economy provided we use plasma. CAP technology helps to use of less dye and increases absorptivity in textiles, can replace washing of food with harmful chemicals to improve shelf-life [115], can replace toxic chemical agents while synthesizing nanoparticles [116], can be utilized in wastewater treatment [117]. Plasma gasification, one of the plasma technology applications, can convert solid waste into monetary and social values for the circular economy [118], however, many research challenges do exist. The liquid

plasma can convert vegetable oils into fuels [119] and thus minimizes the use of conventional sources of energy. Agriculture materials are prone to microbial hazards as they are exposed to dust, animals, and human waste, insects. The plasma technology can reduce these risk factors. The preface of plasma technology for the circular economy faces so many challenges. The best way to bring plasma technology to the circular economy is commercialization after thorough research. There should be a bridge between research and commercialization so that it is beneficial for the successful industrial future. The research should not be limited to the laboratories but should be in profit and money-oriented enterprises on a larger scale. Figure 4 compares the roles of circular economy and plasma technology in achieving the UNDP SDGs. Thus, we can achieve the UNDP SDGs goals if we can utilize plasma technology and cash upon the circular economy.

Conclusion

This review explains briefly the potential of the CAP technology in the food, disinfection, and textile industries. These days, CAP is gaining attention because it is eco-friendly with no release of toxic residue and the main motive of this review is to synergize the underutilized plasma technology for the benefit of the circular economy and implementation in various industries after careful evaluation of the process parameters. A miniscule but active change can be beneficial for the society and environment where the industries can be eco-friendly with abundant financial gains. Especially, in the fast-moving consumer good (FMCG) sectors such as food and textiles, the minimal use of chemicals through plasma technology can help in organically extending the shelf-life and improve the quality of the textiles. Cost-benefit analysis determines whether the technology is effective in terms of economics. For example, compared to alternatives, plasma technology is more efficient than conventional flue gas treatment, which is a post-combustion treatment in terms of investment and operational cost. Moreover, plasma is used for various environmental applications such as air

pollutant treatment, drinking water treatment, and waste treatment in terms of capital expenditure and operating costs plasma technology is more economically viable [120]. Though some ambiguities exist in the implementation of plasma technology in these industries, it is evident that these can be easily overcome with the research findings and cold plasma can be a ground-breaking and cost-effective technology.

Author contributions

KS conceptualized the work, and KS, Re, HB, and RK have written the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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