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Effectiveness of various plasma treatments on nutrient retention and food quality: A comprehensive review of applications and impact

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ABSTRACT

The growing need to find non-thermal processing technology has increased the pace of research on minimal processing, high-quality, and safe foods. Cold plasma (CP) has been one of such techniques, and it is promising as an environmentally friendly and energy efficient method with the ability to decontaminate food surfaces without affecting nutritional and sensory properties. This review thoroughly addresses the concepts, operation and various discharge setups of CP such as dielectric barrier discharge (DBD), corona discharge (CD), plasma jet (PJ), gliding arc discharge (GAD), microwave plasma (MP) and plasma-activated water (PAW) and its application prospects in food processing and preservation. The principles of the plasma generation and microbial inactivation mechanism are described, and it is highlighted that the reactive oxygen and nitrogen species (RONS) have a significant role in the process of adequately decontaminating. The effects of CP in the critical alteration of the major food components: proteins, lipids, carbohydrates, bioactive compounds are critically discussed, which proves the ability of the compound to change the physicochemical, rheological, and functional properties without significant thermal damage. Besides, the review indicates the versatility of CP in increasing shelf life, enhancing extraction performance, increasing starch and protein structures, and countering microbial and enzymatic degradation. Plasma efficacy is also addressed in terms of factors such as processing parameters, gas composition and characteristics of food matrix. In spite of the enormous industrial potential of CP, issues of equipment design, discharge uniformity and regulatory validation still exist. All in all, CP is a viable and controllable technology that unites food safety and quality preservation, and it gives a modernized alternative to traditional thermal treatments as well as establishing the future generations of food processing technologies.

1. Introduction

Food processing industry is in search of new technologies to boost the safety of the products, sell life, and optimise the quality of food in relation to the rising demand of the consumers to high quality products. Heat treatment is a fairly inexpensive and widespread technology in the food industry, known to destroy nutrition, flavour, colour, and texture of food items that are susceptible to heat (Chacha et al., 2021; De Corato, 2020). Non-thermal technology has recently seen extensive application in the food sector because of its low processing temperature to counter the disadvantages of thermal processing technology (Pérez-Andrés et al., 2019). The new technologies are skillful in avoiding such valuable properties as modified food texture and sensory properties, pigment degradation, vitamin loss, the formation of unwanted substances and reduced energy use (Kamankesh et al., 2021). Researchers are exploring these technologies because consumers increasingly demand high-quality, naturally processed meals (Mollakhalili-Meybodi et al., 2021). Over the last two decades, the food industry has shown a great interest in non-thermal processes, as they are efficient and gentle. These substitute technologies can enhance food's shelf life and functionality while mitigating their significant impact on natural flavour and nutrients (Huang et al., 2019). Non-thermal processes enhance bacterial food safety without significantly compromising food quality, thereby preserving the natural flavour and aroma of foods, in contrast to heat

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treatment (Charoux et al., 2021). Ozone processing, high-pressure processing, ultrasound, infrared heating, ohmic heating, pulsed light, dielectric heating (including microwave and radiofrequency), pulsed electric field, and cold plasma are some of the new processing techniques being developed that maintain the majority of the quality attributes. These new methods enable the preservation of food sensory qualities to the greatest extent possible with minimal treatment, thereby protecting food bioactive chemicals and their activity for a longer period (Jiang et al., 2022). Over the last decade, the use of plasma has gained extensive applicability in the food industry as a relatively new and promising non-thermal decontamination technology.

The term "plasma" was first introduced by Irving Langmuir in 1928 to describe the fourth state of matter. Gases on total or partial ionisation produce this plasma. He defined it as an area where the electrical charges of electrons and ions are balanced. In addition to atoms in their basic excited form with neutral charges, it can be considered a quasi-neutral medium consisting of free electrons, ions and photons (Sasikumar et al., 2025). The primary characteristic of a plasma is its propensity to remain practically electrically neutral, signifying that the quantity of electrons as well as ions is approximately equal at all locations in space. This occurs due to electrons possessing a significantly high charge-to-mass ratio, whereby even a little charge imbalance generates an electric field sufficiently enough to rapidly draw electrons back towards the positively charged area (Beckers et al., 2023). If even 1 % of the charges dissociate in a plasma having a density of 10^{11} cm^{-3}, it would produce an electric field of around 150 V/cm. A robust field might accelerate electrons at an extraordinary pace (10^{17} cm/s^2), prompting them to swiftly return and rectify the imbalance practically instantaneously. Nonetheless, due to the inertia of electrons, they do not cease motion instantaneously but rather overcharge and oscillate at a considerably greater frequency around the equilibrium state. Consequently, the plasma remains quasi-neutral on average, despite the presence of minutes, rapid oscillations (Lebedev & Mokeev, 2003; Thompson, 2013). Debye shielding refers to the phenomenon in which free charges in a plasma reorganise around a test charge, thereby diminishing its electric field and limiting its effect to its own Debye length (Fitzpatrick, 2022). This guarantees that, beyond this minimal distance, the plasma exhibits electrical neutrality. Consequently, Debye shielding serves as the microscopic process that upholds the plasma's overall quasi-neutrality, with charge imbalances occurring just on a local scale rather than on a broader one (Hasani, 2023). To preserve the quality and safety of food, cold plasma (CP) is a new technology solution (Ucar et al., 2021). The technology is not just used in the food industry; it is also used in the textile industry (Sahani, 2024; Vajpayee et al., 2025; Hemmatzadeh et al., 2024), the sanitisation of heat-sensitive biological and chemical agents (Subrahmanyam et al., 2024), the environmental degradation of waste and toxic residues (Cyganowski et al., 2024), and the surface decontamination of medical devices and environments (Nwabor et al., 2022; Hage; Koga-Ito et al., 2024; Bende et al., 2024). Furthermore, before the food sector accepts CP as a new food processing alternative, it must be thoroughly assessed. In this process, food pollutants, including microbiological cells, enzymes, and toxins, are inactivated with the help of plasma that is a type of ionised or partially ionised gas (Dalvi-Isfahan & Mahmoodi-Eshkaftaki, 2024). The main elements of plasma are free radicals; hence, the plasma is produced by sufficiently heating gas in an enclosed chamber under a deep vacuum or by employing radiofrequency or microwave energy to excite the gas molecules (Gulka et al., 2024). According to Fernandes and Rodrigues (2025), CP is produced by releasing air or inert gases, such as argon, nitrogen, and helium, under either vacuum or atmospheric pressure. The active plasma species (such as active nitrides and active oxides) produced during processing can effectively kill microorganisms on the food surface and cause changes in the food's functional characteristics. CP is favored as compared to other methods owing to its many applications and benefits. As an example, it is a thermodynamic non-equilibrium condition, and high reactivity is beneficial to various industries, such as food, medicine, agriculture, and packaging (Niveditha et al., 2021). This non-thermal process produces several reactive species, including singlet oxygen ($^1O_2$), nitric oxide (NO), peroxynitrite ($ONOO^-$), superoxide (O_2^-), atomic oxygen (O), hydroxyl radical (OH), hydrogen peroxide (H_2O_2), atomic hydrogen (H), ozone (O_3) and hydroperoxyl radical (HO_2), interacting with water molecules to simultaneously produce shockwaves and light emissions (Ishmael et al., 2025). In particular, OH radicals and other reactive species can be generated using non-thermal plasma without the need to spend money on costly chemicals or ultraviolet lamps (Bakhtiyari-Ramezani et al., 2025). It has also been used in other areas of the food industry, e.g., on the appearance of food packaging material (Hage et al., 2022; Tahmouzi et al., 2025), degradation of pesticides and toxins in food (Sreelakshmi et al., 2025; Sojithamporn et al., 2023; Wang et al., 2023) and microbiological purification of food (Thakur et al., 2025; Zheng et al., 2025). Thus, based on all these arguments, CP technology is proliferating very fast and is catching the attention of technologists in the food processing industry (Jiang et al., 2014). However, the studies on the CP treatment impact on food quality attributes and functional components are yet to be implemented. Therefore, this review aims to provide food researchers, technologists/engineers, and industrialists with more information that may support and facilitate the efficient comprehension and application of the CP technique in food preservation, thereby improving food safety.

2. Cold plasma (CP) technology

Cold Plasma (CP) is a new non-thermal process that has shown great promise in the food industry. Previously, CP was primarily used in the electrical and polymer industries to modify surfaces and functionalise various polymers. The latest developments in CP have accelerated its use in various biomedical devices and biological material treatments, including food (Pankaj & Keener, 2017). Plasma is an ionized gas that is created when molecules and atoms are thermally or non-thermally ionized into cations, free radicals, free electrons and anions, expelled molecules and atoms and electromagnetic radiation (such as ultraviolet light) (Pan et al., 2019). The ionized molecules, atoms and free electrons are going to be in a non-equilibrium state (non-thermal or CP within 60 °C), a quasi-equilibrium (plasma in low temperature: approximately 100–150 °C) or a thermodynamic equilibrium (thermal plasma) based upon the energy source given to the gas (Misra et al., 2016a). Hence, it is classified into two primary categories: "thermal plasma, also known as quasi-equilibrium plasma and "non-thermal plasma, also called non-equilibrium plasma". Thermal plasma is created when ions are generated using thermal energy (about 20,000 K).

Plasmas in non-equilibrium and quasi-equilibrium states are created by ion production from relatively warm energy sources (Warne et al., 2021). CP, also called non-thermal plasma, is primarily mentioned as plasma during non-equilibrium conditions. The electrons in this state have been powerfully energized (electron temperature $T_e \sim 10^4$–10^5 K), but because of their relatively small size and distance from the nucleus, there has been relatively little thermal energy transfer from the entire plasma (Heavier particle temperature $T_h \sim$293 K–423 K) (Zhang et al., 2019). The relative temperatures of neutrals, ions and electrons can be used to classify plasma. In thermal plasma, the heavier particles and electrons have thermal equilibrium, meaning they have the same temperature. However, the electron temperature in non-thermal plasmas is relatively high (≈ 10,000–100,000 K; glow discharges), while heavier particles, such as neutrals and ions, have lower temperatures, sometimes even room temperature (Reema et al., 2022; Pankaj et al., 2018a). Thermodynamic equilibrium is shown by all species of thermal plasma (e.g., heavier species temperature ≈ electron temperature ≈ 10,000 K; arc plasma). However, in different plasmas, all species exhibit the same temperatures in some areas of the plasma. CP's lower temperature is a helpful tool to reduce nutrient loss, but it can also alter macromolecules due to its high energy (Han et al., 2019). Non-thermal plasma is also called non-equilibrium plasma because its production requires lower pressures and powers without maintaining local thermodynamic equilibrium. The energy imparted to the gas causes it to dissociate into several reactive species, which then undergo additional reactions, including ionisation, excitation, and de-excitation (Ekezie et al., 2017a). Although both plasmas have found applications in various fields, the one that has caught the attention of the food industry is non-thermal plasma due to its high flexibility and low energy requirements (Olatunde et al., 2023). Alternatively, plasma is categorised as low-pressure, high-pressure, or atmospheric-pressure plasma based on different pressure conditions. Since atmospheric pressure plasma can be produced at normal atmospheric pressure, costly reaction chambers are not required to maintain pressure (Pankaj & Thomas, 2016). CP typically comprises neutral atoms, activated molecules, free radicals, and ions of both negative and positive charges. CP is created upon exposure of gases such as argon (Ar), hydrogen (H_2), oxygen (O_2), helium (He), nitrogen (N_2), carbon tetrafluoride (CF_4), neon (Ne), methane (CH_4), ammonia (NH_3) to electric fields like thermal, direct current (DC), alternating current (AC), radio frequency (RF) magnetic fields and microwave using atmospheric temperature (Thirumdas et al., 2017, 2015). Radio frequencies, dielectric barrier discharge, gliding arc discharge, inductively coupled plasmas, microwave-induced plasma, corona glow discharges, and atmospheric glow discharge are a few techniques used to produce CP (Farooq et al., 2023).

3. Mechanism of cold plasma (CP) generation

An alternating magnitude (often a high-frequency field) or a continuous (DC field) plasma is created by exposing gas to an electrical current (between two electrodes). The plasma state is achieved by applying energy in various forms, such as electric, thermal, microwave, or radio frequencies. This raises the momentum of the electrons, causing more collisions of gas to form plasma elements, such as ions, electrons, radiation, and radicals, with different wavelengths, including the UV range (Thirumdas et al., 2015). In CP treatment, energy circulation in other particles is primarily irregular (a non-equilibrium), which determines the specific matrix's electron component. An electron is more prone to transfer heat through impact with heavier particles in CP. Different non-thermal plasma discharge techniques are employed depending on the mechanism and intended target reaction (Harikrishna et al., 2023). There are several ways to create CP, including gliding arc discharge (which are often non-thermal ($T_e \gg T_h$) and may exhibit local thermal equilibrium (LTE) at high currents) (Fridman & Kennedy, 2004), dielectric barrier discharges (DBD), radio frequency plasma (RFP) and corona discharge (CD). Radio frequency (silent discharges) and low-pressure DC discharges, as well as discharges from fluorescent tubes (such as Ne) and DBD, serve as examples of CP that utilise both low-pressure and ambient pressure (Thirumdas et al., 2015). The terms "gas breakdown" and "electron avalanche" refer to fundamental processes that convert a non-conductive gas into an electron-conducting medium. The Townsend discharge signifies the preliminary phase of electrical breakdown in gases, occurring as free electrons acquire sufficient energy from an applied electric field to ionise neutral gas molecules. The electric field tends to be weak, allowing the electron mean free path to be sufficiently lengthy for electrons to speed up between collisions, yet not so extensive that collisions become infrequent (Sammut, 2025). The process begins with primary ionisation, in which energetic electrons collide with neutral molecules, ejecting additional electrons and generating positive ions. The secondary electrons are further accelerated, perpetuating the avalanche phenomenon (Xiao, 2016). Concurrently, secondary ionisation occurs when ions or photons produced during the discharge impact the cathode surface, releasing additional electrons that perpetuate the avalanche. The combination of these main and secondary processes creates a self-sustaining current under low pressures and moderate electric fields, typical of the Townsend discharge regime (Thagunna, 2024). In an electron avalanche, many positive ions and electrons are produced when electrons accelerate in the electric field and collide with other molecules and atoms, ionising them. Electrons (10^5–10^6 m/s) travel towards the avalanche head, whereas positive ions (50–500 m/s) flow towards the tail due to their higher speed and lower mass. Ions draw new electrons from the cathode surface, forming subsequent avalanches. If ionisation is severe enough, the gas is disrupted and turns conductive (Bruggeman et al., 2017; Conrads & Schmidt, 2000; Misra et al., 2016b; Xiao, 2016). Table 3 discusses the comparison of different plasma sources and their typical applications.

3.1. Dielectric barrier discharge (DBD)

DBD is growing in importance in the plasma production scenario because it is more cost-effective at the industrial scale than other methods. The dielectric material, the flexibility of the electrode shape, and its configuration make this technology a convenient form for generating plasma with several applications (Misra et al., 2019). Since a pulsed DC-driven DBD type occurs when a dielectric barrier is applied to the discharge area, the samples can be handled directly or indirectly. The operational range of DBD is extensive, operating over a range of frequencies and voltages. To obtain a more homogeneous distributed plasma, it uses a combination of different gases, characterised by short-lived microdischarges in large numbers (Chen et al., 2020). An electrode is connected to the ground, while another electrode is linked to a circuit with a high voltage. There is an uneven AC or DC discharge that typically operates between 0.05 and 500 kHz, spanning a broad gas pressure range (generally between 10^4 and 10^6 Pa) and with operational energy needs between 10 and 100 W (Zhang et al., 2017; Shimizu et al., 2019). Some of the parameters that are known to influence the efficiency of DBD are the gas applied, the distance between electrodes and the operating voltage. Dielectric barrier discharge is the plasma source that is best used on larger surfaces (Harikrishna et al., 2023). The parameters of DBD operation are in the range of (i) AC or DC with a voltage amplitude that reaches 10 as well as 100 units, (ii), band of frequency which varies between 10 and 50 MHz, and (iii) pressure of gas between 1×10^4 and 1×10^6 Pa (Feizollahi et al., 2021). The advantages of DBD approach are that it is possible to produce a plasma using a broad assortment of gas types, different shapes of electrodes, and in addition, produce plasma with low or no gas flow. It is a good application in processes with massive surfaces (Phan et al., 2017). This is extremely unfavorable as it needs an electrical current of at least 10 kV to operate (Deshmukh et al., 2022). Fig. 1 illustrates the application of DBD in the processing of wheat. DBD plasma has also been widely studied in the modification of proteins and inactivation of bacteria in food systems, and new uses in processing. When comparing single (S-DBD) and double (D-DBD) reactors, Yang et al. (2025b) found that S-DBD had a higher discharge intensity and reactive species generation, and therefore, it had greater pathogen suppression than D-DBD. In particular, 4 min *Salmonella typhimurium (S. typhimurium)* and 0.94-$\log_{10}$ and 0.94-$\log_{10}$ *Listeria monocytogenes* (L. *monocytogenes*) were treated with S-DBD plasma at 80 W with the maximum reduction of 3.52-$\log_{10}$ and 0.94-$\log_{10}$, respectively. D-DBD plasma, in contrast, had a lower reduction of 0.82-$\log_{10}$, 0.78-$\log_{10}$ of the same pathogens. Similar findings were in Lemos et al. (2025), who demonstrated antifungal activity of DBD plasma against bread spoilage fungi, which showed fungistatic activity (increased mycelial growth inhibition of up to 30 days) and fungicidal activity (enhanced fungal growth inhibition activity at the higher levels of power and exposure) leading to complete elimination of *Penicillium sumatrense* and up to 7 log reductions in pan bread slices. A similar effect in demonstrating the antifungal effect of DBD plasma was shown by Lemos et al. (2025), which showed fungistatic effects extending mycelial growth inhibition up to 30 days and fungicidal activity at high levels of power and exposure, with full eradication of *Penicillium sumatrense* and 7-log reductions in pan bread slices. In addition to microbiological safety, DBD plasma has demonstrated potential in non-thermal thawing applications. Atani et al. (2025) indicated that DBD plasma thawing

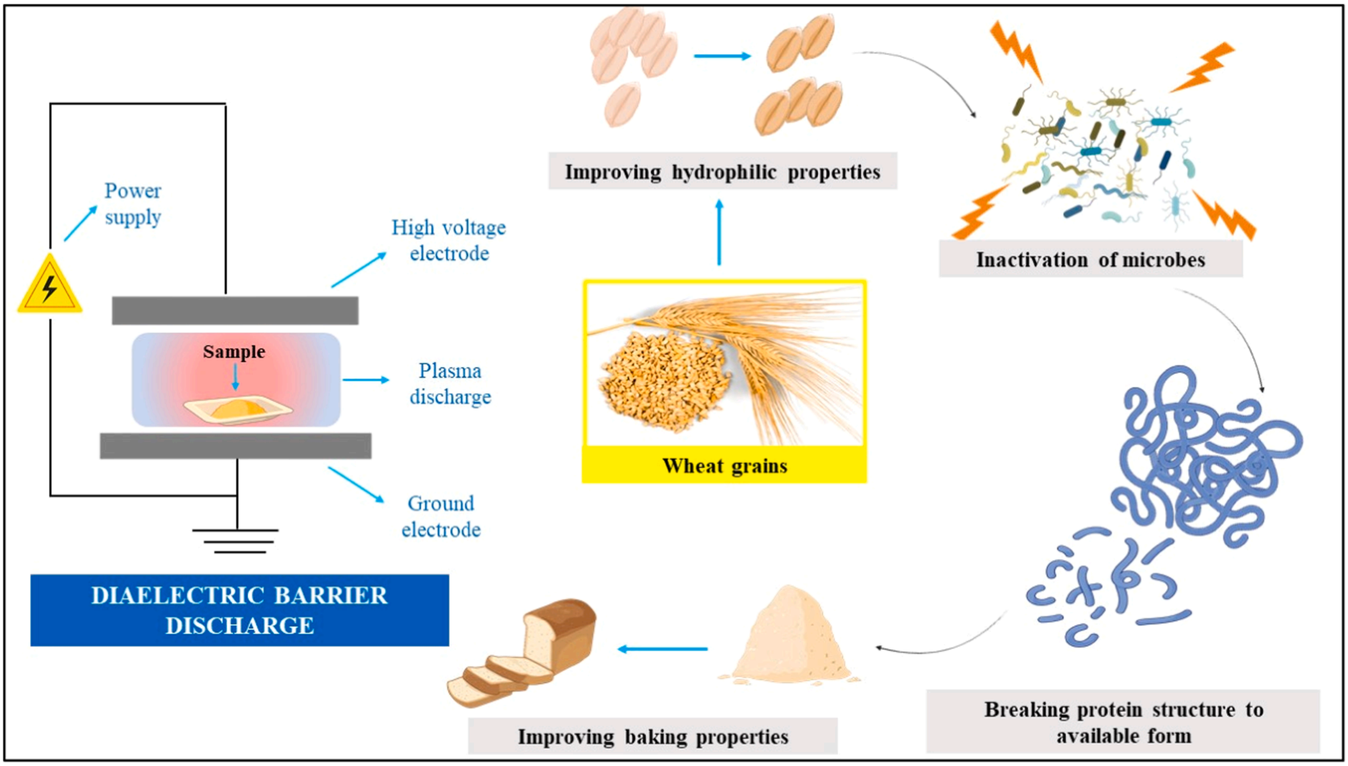

Fig. 1. DBD in wheat processing.

decreased beef thawing duration by 82 % compared to still-air techniques and utilised as much as 95 % less energy than microwave thawing, thereby improving energy efficiency by approximately 50 %. Significantly, plasma-thawed beef exhibited minimal microbiological proliferation and maintained cytotoxicity safety, despite elevated voltages modified myofibrillar protein makeup and microarchitecture. These findings collectively underscore DBD plasma as a multifaceted technique that enhances protein functionality, ensures microbiological safety, and facilitates quick, energy-efficient food thawing.

3.2. Plasma jet (PJ)

PJ is categorised as a type of plasma generated with the help of Radio Frequency (RF). Atmospheric pressure plasma jets (APPJ) commonly refer to this type of plasma. The plasma ejection is under constant atmospheric pressure, making it homogenous and steady (Kumar et al., 2024). Another plasma source creates the plasma in this different configuration, which is employed to discharge the plasma jet (Coutinho et al., 2018). This type of plasma features a concentric arrangement of electrodes. The gas passes between the two electrodes. When the outer electrode is grounded and the inner electrode is subjected to a high voltage (100–250 V) and a high frequency (radio frequency of 13.56 MHz), the passing gas is ionised. The field created alongside the radio frequency excites free electrons, resulting in plasma production by inelastic collision (Misra et al., 2016b). The carrier gas helps approach the excited species towards the electrode terminal or exit through a small valve. Noble gases, such as Ar or He, are primarily used in this procedure, but at higher flow rates (>10s/m) (Harikrishna et al., 2023). Interaction occurs in the target gas working chamber, causing it to ionise and exit a nozzle with a "jet-like" appearance (Zhang et al., 2015). A unique feature of APPJ is that it eliminates the size constraints for the treated sample as it operates in open space. The plasma jet extends to a length greater than 10 cm, demonstrating its high flexibility. Plasma is enriched with free radicals, ultraviolet radiation, and a diverse chemical mixture, emitting heat and charged particles (Li et al., 2024). In contrast to low-pressure plasma, APPJ does not require a vacuum setup, making it a cost-efficient process. The architecture of APPJ is created in such a way that it forces the plasma through a powerful flow of air and it is released into the environment. Also, the operating safety with the extension of the distance between plasma and high-voltage electrodes is enhanced (Chen et al., 2020). Under some non-equilibrium conditions, the temperature of the room can be approximately equal to the temperature of the gas in the plasma, which has extended the use of APPJ in surface material treatment, film deposition and biomedical applications. This underscores the high benefits and flexibility of APPJ (Li et al., 2024). The drawback of this plasma is that in spite of its effectiveness, its coverage is smaller and the large areas of surface require the placement of multiple jets (Bermudez-Aguirre, 2019).

APPJ has shown a lot of efficiency in eliminating microbes and spores in different food systems. Liu et al. (2023) showed that the use of air-APPJ gave a reduction of more than 2 log CFU /g of spores in optimal conditions (50 L/min, 800 W, 10 cm, 20 min) compared to heat treatment, with no significant effect on colour and flavour. Abdullah et al. (2024) reported that air-APPJ administration to white bread (13.6–16.2 kV, 120 s) significantly reduced mould development during a seven-day storage period, decreasing mould incidence from 68.88 % in controls to 21.39 %. Liu et al. (2024) demonstrated that APPJ inactivates spores chiefly via oxidative stress, leading to the peroxidation of essential lipids of the membrane (phosphatidylglycerol, phosphatidylcholine, cardiolipin), hence compromising membrane integrity and enhancing permeability. These investigations collectively demonstrate that APPJ is a reliable non-thermal method that efficiently diminishes spore-forming and fungal pollutants while preserving overall food quality.

3.3. Corona discharge (CD)

The ionisation of gases occurs due to the bombardment of high-voltage power from non-homogeneous electrodes (Kumar et al., 2024). For plasma ignition, the diffused route is by corona discharge plasma. This forms near sharply pointed electrodes, creating an electric field that is significant for speeding up the ionisation energy of casually generated electrons to environmental gas atoms or molecules (Scholtz et al., 2015). This type of emission is characterised by an asymmetric electrode pair, where a plane and a point are formed in a limited geographical region due to threshold breakdown caused by an excess of the electric field. A weakly ionised plasma is created when the electrode near a high electric field crosses the breakdown strength of the gas (Laroque et al., 2022). Significant energy is gained by electrons near the electrode, resulting in an avalanche effect of electrons due to the ionisation of gas molecules through collisions and subsequent electron production (Li et al., 2024). Under atmospheric pressure and non-uniform electric field strength, plasma production occurs in this process (Zainal et al., 2015). This phenomenon is frequently observed around the conductors, such as the blue-purple corona and the border of the strong electric field. This is a specific, self-sufficient gas discharge medium in an inhomogeneous electric field (Dey et al., 2016). Uneven distribution of the electric field, an applied voltage of several thousand volts or more to the electrodes, and high gas pressure are all factors that can lead to CD. As a result, two parallel electric lines will form from the electrodes, creating a corona and a non-uniform electric field (Zhang et al., 2022). Energy discharges at the electrode's end and flumes unevenly due to the electrode's shape. An active electrode is the one on which the corona emits (Kumar et al., 2024). The main energy of the CD acts on the surface material through neutral molecular flow, light radiation, and ion flow. The system operates in direct current or pulse voltage current mode, eliminating the need for complicated machinery and reducing operational costs. One significant drawback of this approach is the non-uniformity of treatment (Coutinho et al., 2018). For application in the food sterilisation process, corona discharge is considered the most suitable choice (Nisha et al., 2019). Fig. 2 depicts the application of the CD system. CD plasma technologies exhibit significant potential for enhancing agricultural and food products via structural alteration, improved drying efficiency, and quality improvement. In soy protein isolate, mild corona discharge at 14 kV for 90 min unfolded protein structures, enhancing solubility (31.75 %) along with surface hydrophobicity. In contrast, elevated voltage (18 kV) facilitated aggregation via α-helix & β-sheet production (Tan et al., 2024). High-voltage corona discharge (HVCD) pretreatment of alfalfa enhanced both drying and rehydration rates, increased crude protein content, and improved the nutritional value of the forage by altering fibre structures and inducing electroporation, while consuming less energy than conventional drying methods (Guo et al., 2024). In lilies, CP corona discharge expedited drying kinetics, decreasing the drying duration to 7 hrs (CD plasma-3 min) and elevating the total phenolic content as well as antioxidant activity, accompanied by microstructural alterations such as micropore development associated with improved bioactive preservation (Wang et al., 2024). These data collectively demonstrate that CD plasma serves as an effective non-thermal pretreatment method to improve drying efficiency, structural alteration and nutritional quality in various biological materials.

3.4. Gliding arc discharge (GAD)

When a reactor has at least two separate metal electrodes operating at a high voltage contrast of 9 kV and 100 mA, gliding arc discharges (GAD) can occur (Ekezie et al., 2017a). The discharge space between electrodes is usually filled with a mixture of entering gas and humid air. Consequently, a shortest inter-electrode region creates an arc, blown out by the incoming gas, into the diverging one (Scholtz et al., 2015). The gas is fed from the wider top inlet, travels downward, and is simultaneously released at the narrower arc electrode by a stronger electric field that is supplied. Movement of plasma to the substrate is aided by the airflow at the end (Muhammad et al., 2018). Depending on the configuration, GAD may generate either a heated or non-thermal plasmas. Besides assisting in operational studies, such as the disintegration of contaminants such as industrial waste, organic matter, and solvents present in water, decontamination of bacteria, scientists have used the process in the liquid and surface treatments (Scholtz et al., 2015). In any shape or size of the product, gliding arc plasma is accomplished by using a knife-shaped electrode which is curved at the bottom to offer a plasma

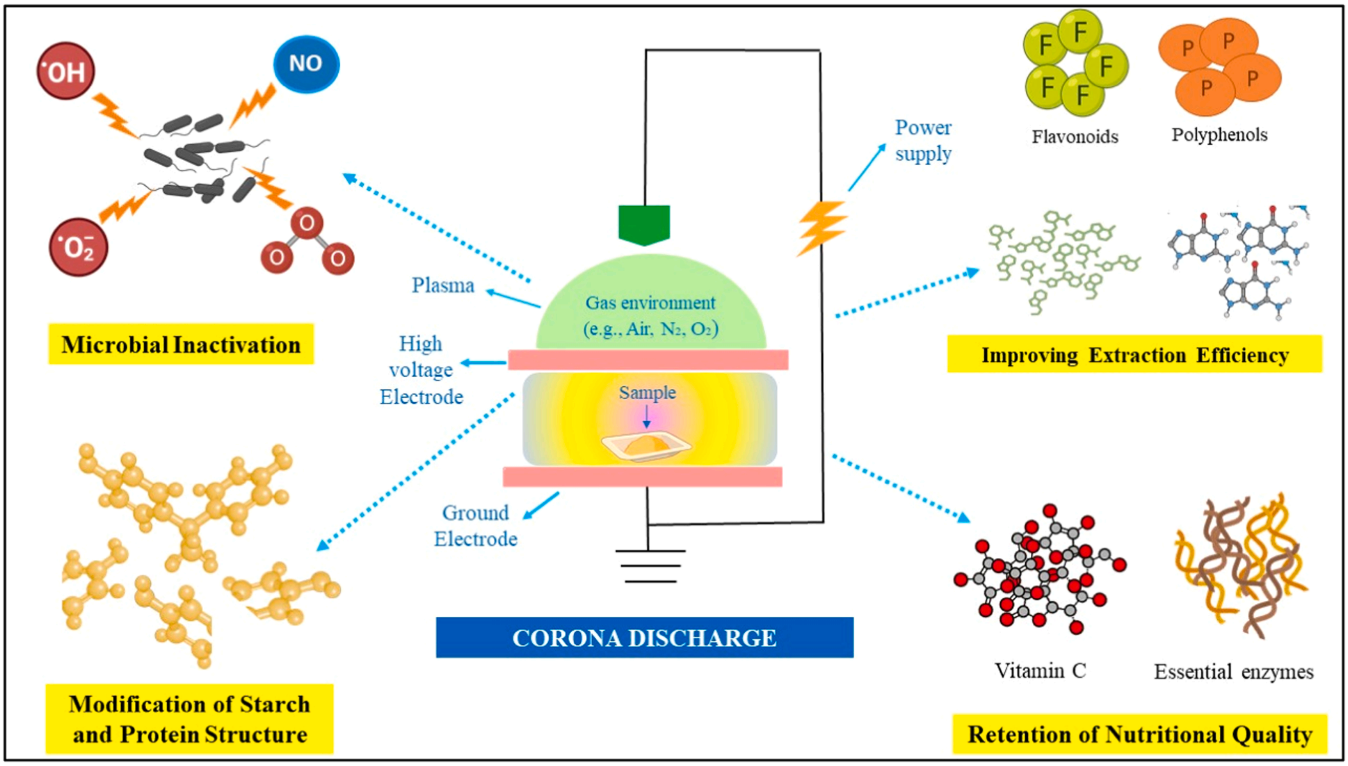

Fig. 2. Application of corona discharge.

action. The generation of GAD makes the measure of non-equilibrium (thermal) greater (Deshmukh et al., 2022). This device comprises separating electrodes with “knife-edges”, a nozzle, impedance, a high-power supply and an insulating cover. The arc discharge is created with an electric current of around 3 kV mm^{-1} (Chaitradeepa et al., 2023). Plasma discharge begins at the short end when electrodes with opposing polarities are brought together and connected, expanding between the inter-electrode lengths. When the arc exceeds the critical value, the non-equilibrium phase starts. When the energy supply from the power source exceeds the limit, heat loss occurs in the plasma column. CP is produced when plasma is rapidly cooled (Khalili et al., 2018). GAD allows rapid processing. The outcome of this procedure is greatly influenced by the temperature of the electrode and discharge (Deshmukh et al., 2022). Cold atmospheric GAD plasma has demonstrated potential applicability in various food systems. GAD diminished 5-hydroxymethylfurfural in honey by as much as 37 %, concurrently decreasing free acidity, moisture, overall yeast counts, while maintaining diastase activity, antioxidant capacity and phenolic content, so demonstrating its appropriateness for non-thermal honey treatment (Onal-Ulusoy, 2021). Likewise, low-temperature GAD pretreatment improved blueberry drying by decreasing drying time by 31.25 %, augmenting phenolic content by 33.47 %, and enhancing rehydration capacity by 27.94 %, while preserving anthocyanins alongside additional bioactive compounds, thereby endorsing its feasibility for large-scale industrial drying (Yu et al., 2025). GAD treatment in black pepper diminished aerobic bacteria by 73 %, yeast and moulds by 93 %, and fully inactivated the *Bacillus cereus* exemplar strain, while exerting minimal effects on piperine and volatile oils, underscoring its efficacy in microbial decontamination without compromising quality (De Silva et al., 2025).

3.5. Microwave plasma (MP)

Plasma is induced electrodelessly in a microwave generator. The power in the microwave region is transported via a waveguide, and impedance-matching equipment is in the tuning section. Through a nozzle positioned where the strongest electric field is found, operating gas is introduced (Chen et al., 2020). MP is produced at frequencies between 300 MHz and −10 GHz (Kumar et al., 2024). MP is the finest plasma source for surface modification because of its low energy in the generated plasma ions (Kusano, 2009; Deshmukh et al., 2022). Plasma discharges generated by magnetrons are propelled by a high-energy electromagnetic field, usually at 2.45 GHz. Low pressure and air pressure can both be used to create plasma (Laroque et al., 2022). The gas electrons become more energetic after absorbing the microwave. Increased kinetic energy in electrons causes inelastic collisions, which in turn cause gases to ionise (Apte & Bhide, 2024). Typical advantages of ionised gas include an increase in electron density and an increase in the efficiency of reactive species formation. This technology also does surface sterilisation or decontamination. Due to its high operating costs and maintenance requirements, it is not used very often (Ekezie et al., 2017b; Bermudez-Aguirre, 2019). Fig. 3 depicts the mechanism of microwave discharge. Despite the scarcity of focused research on microwave-induced plasma (MIP) in food chains in recent years, the microwave plasma approach has demonstrated efficacy in microbial inactivation on desiccated surfaces such as spices and dried fruits (Kasar et al., 2024). Mandarins subjected to microwave-powered cold plasma treatment (900 W, 10 min) demonstrated increased antioxidant and phenolic content in the peel, indicating quality improvements that are not controlled by microbes (Sharma et al., 2025). Likewise, MP treatment considerably reduced microbial burdens, encompassing L. *monocytogenes* and *Escherichia coli (E. coli)* across both raw and cold-smoked Atlantic salmon, without adversely affecting texture, colour, or sensory attributes. Cold-smoked samples exhibited a more significant reduction in microbial presence, but lipid oxidation and protein denaturation were negligible, suggesting its viability as a non-thermal retention method for prolonging the shelf life of salmon (Weihe et al., 2022).

3.6. Plasma-activated water (PAW)

The production of non-thermal plasma (NTP) in atmospheric air

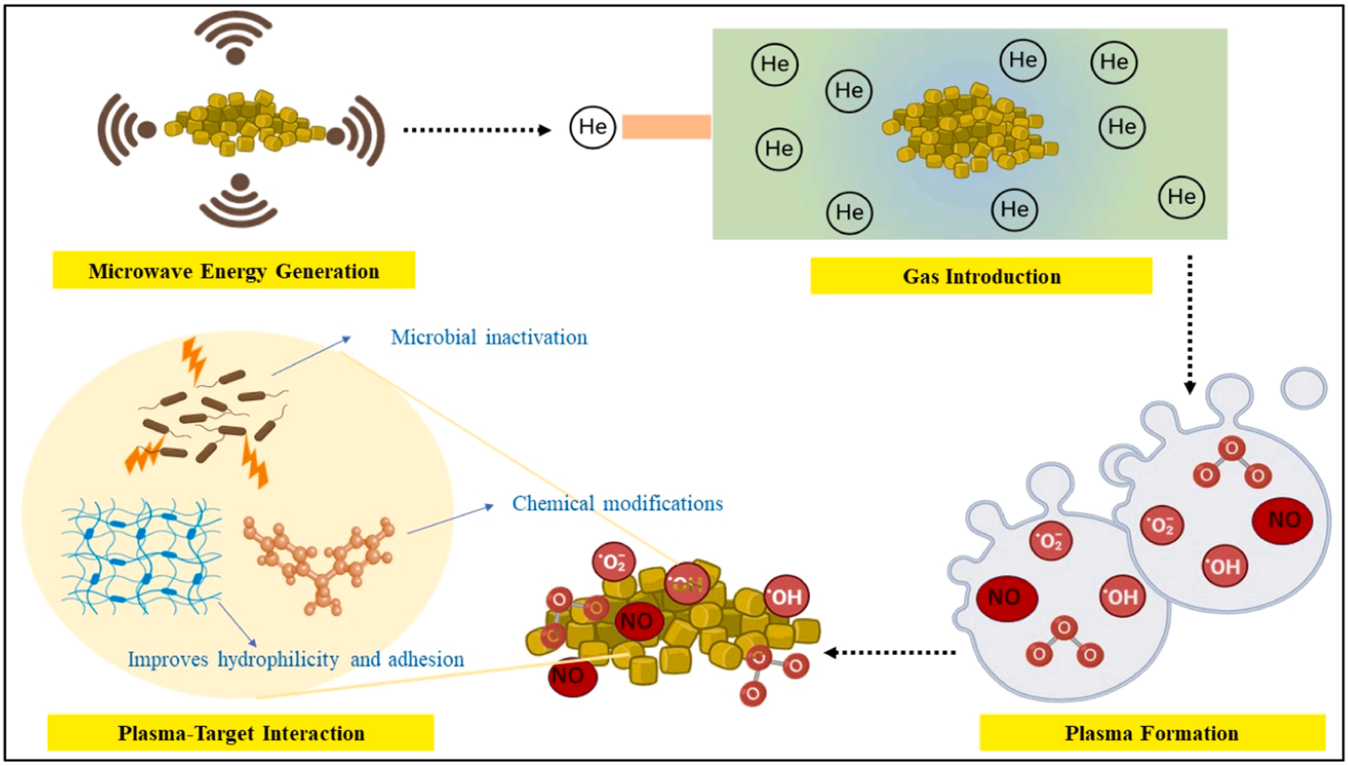

Fig. 3. Mechanism of microwave discharge.

leads to the formation of numerous reactive oxygen and nitrogen species (RONS) due to the abundance of nitrogen, oxygen, and moisture in the environment. Direct NTP-water interaction causes reactive oxygen and nitrogen species to permeate into the water, which results in plasma-activated water being formed (Thirumdas et al., 2018). Long-lived compounds, such as nitrates (NO_3^-), nitrites (NO_2^-), hydrogen peroxide (H_2O_2) and ozone (O_3) are likely to be the main components of the RONS in particulate air water (PAW), and have lifetimes of days, hours and min. Conversely, short-lived species containing hydroxyl radicals (OH•), nitric oxide (NO•), superoxide (O_2-), peroxynitrate ($OONO_2$-), along with peroxynitrite (ONOO-) have lifetimes less than one second. The RONS in PAW lead to the significant physicochemical changes in the properties of water, which are responsible to the inactivation of microbes. All species have their specific role in a variety of PAW applications (Zhou et al., 2020; Misra et al., 2024). It is, therefore, urgent to come up with powerful methodologies of streamlining the RONS composition in PAW to improve its efficiency in other applications. Atmospheric pressure plasma has also become one of the new technologies in the last few years, to produce plasma-activated water (PAW), which has been shown to be effective against numerous microorganisms and does not affect the quality of products to increase food disinfection, storage, and shelf life of fresh vegetables and fruits (Kooshki et al., 2024; Waskow et al., 2022; Subramanian et al., 2020). PAW has become a diverse tool in the food and agriculture sector. PAW extrusion (120 s) treatment increased starch modification by raising amylose and soluble starch concentrations and decreasing maximum viscosity and swelling power in the food industry, which can be used as an innovative method of developing low-glycemic index meals (Niu et al., 2024). PAW irrigation increased plant vigour and decreased tomato susceptibility to two-spotted spider mites by lowering pH, raising reactive oxygen species (H_2O_2, NO_2^-, NO_3^-), and enhancing nutrient uptake and trichome density in agriculture (Savi et al., 2025). Similarly, the microbial burden of whiteleg shrimp and magnificent squid reduced to less than 6 log CFU/ g under the best conditions (13.30 mg/L H_2O_2), using PAW soaking (10 min) but potential oxidative effects occurred on lipids and proteins (Vichiansan et al., 2024). Also, Tang et al. (2025) proved that PAW, when combined with probe-type ultrasonication, influenced the structural and functional properties of shrimp and cod proteins, changing the surface hydrophobicity, sulfhydryl content, and secondary structure. Combined, the findings are suggestive of the twofold impact of PAW in microbial inactivation and control of protein activity, which facilitates its use as a viable technology in bio-food quality and safety improvement. All these results lead to the possibility of PAW as a sustainable solution to improve food quality, food safety, and food resilience.

4. Factors affecting plasma

The efficacy of CP treatment all depends on some variables, such as food variables, microbiological variables and plasma operating conditions. The treatment result can be changed by adjusting parameters such as treatment duration, voltage, working gas makeup and frequency (Nwabor et al., 2022).

4.1. Internal factors

The various types of processing gases, plasma flow rate, processing frequency & voltage are limited intrinsic factors that influence CP processing efficiency. The chemically reactive species formed during processing depend on the type of carrier gas used. Working gases used in CP technology include air, nitrogen, oxygen, helium, argon, or a combination of these. Air is most commonly used because it is the least expensive. During the reaction, numerous reactive oxides and nitrides are produced by air. Organic compounds inside the cell react with this reactive species. Inert gases, being stable in nature, cause minimal changes in the chemical composition of foods (Fernandes & Rodrigues, 2021). The action and efficiency of plasma are affected by gas composition, as it defines the reactive species produced by ionisation (Feizollahi et al., 2021). Food chemical degradation by oxidation can be reduced by using oxygen in combination with an inert gas. A discharge mixture containing oxygen and nitrogen produces peroxy-radicals, nitrogen oxide (NxOy) and ozone. Meanwhile, H, OH and H_2O_2 species are produced when water is present with reactive gases (Gavahian et al., 2018). Input frequency and voltage during the reaction affect the quantity of plasma produced. The effectiveness of CP is influenced by various induction methods and plasmas, each with unique properties. For instance, the form in which processing gas is used determines the amount and kind of reactive species generated by discharge and the treatment effectiveness (Guo et al., 2015). Direct mode of exposure to CP increases its efficiency compared to remote or indirect exposure, as the quantity of heat conveyed to the matrix decreases, thereby decreasing efficiency (Patil et al., 2014).

4.2. Microorganism factors

The intrinsic characteristics of microorganisms also have an impact on the efficiency of CP. The internal characteristics of the microbe are crucial for achieving a higher level of process efficacy during microbiological decontamination of food, as sensitivity can vary among strains or species (Lunov et al., 2016; Yong et al., 2015). The tremendous antibacterial effect of plasma can deactivate many microbes, including yeasts, viruses, and both Gram-negative & Gram-positive bacteria. Bacterial RNA & DNA can be altered by oxidative destruction, strand breaking, & alteration of bases, while plasma targets and destroys different microorganism structures, such as etching cell walls, peroxidising lipids, and dissolving biofilms. Additionally, large molecules may be modified or unfolded; this is a specific plasma sterilisation process. CP has shown promising results in various fields (Jiang et al., 2022). In comparison to other treatment processes, plasma treatment is resisted by sporulated bacteria rather than vegetative cells, increasing the attentiveness of bacterial cells while reducing the penetrative effect of reactive species. The cell walls of fungi exhibit greater resistance to plasma treatment than those of bacterial cells because the fungal cell wall is composed of chitin Ekezie et al. (2017a).

4.3. Milieu factors

The matrix of sample, pH, time, relative humidity, and condition of exposure are factors that significantly affect the efficacy of CP treatment. For example, the liquid and solid food substrates react differently with the reactive species during CP processing. All the components are in complete contact with plasma species in the liquid food. In solid matrices, the penetration rate of active particles is affected by composition, moisture content of the food, and porosity (Ekezie et al., 2017a; Surowsky et al., 2016). The plasma's velocity, reaction with the food matrix, and the half-life of the reactant species all affect the final benefit. Increased humidity in plasma surroundings can enhance the activity of chemicals such as superoxide anions, peroxyl radicals, hydrogen peroxide, and other reactive oxygen species (ROS), thereby increasing oxidation and antibacterial properties (Surowsky et al., 2016). ROS were initially recognized as toxic by-products of aerobic metabolism, removed by means of antioxidants and antioxidative enzymes and these negative ions are formed when electrons and water molecules interact in air with relatively high humidity (Banerjee & Roychoudhury, 2017). The low speed of negative ions in an electric field reduces the ionisation probability, as fewer electrons form an avalanche, necessitating a greater breakdown voltage than at a high concentration of water vapour. Decomposition of water molecules into H_2 and O_2 gases. The distance and pressure between electrodes (*pd* product) determine the reduction in voltage regarding the H_2 concentration (Xiao, 2016). Meanwhile, the type of matrix affects process efficiency. For example, a filter membrane or an agar plate can be decontaminated more effectively than a cheese slice or a fruit surface, as microorganisms move from outer to inner tissues at a specific rate (Yong et al., 2015).

5. Effect of CP on food

The potential of food is determined by the impacts of CP treatment on its colour, flavour and aroma. The quality, nutritional value and sensory qualities can vary depending on exposure conditions, time and CP process residues (Pasquali et al., 2016). Nutrients are preserved since lower penetration impacts only the surface (Mandal et al., 2018). The effect of CP on various attributes and the impact of different types of plasma treatment on different types of food are discussed below.

5.1. *Effect on organoleptic properties*

With the help of analytical measurements and sensory trials (texture, moisture content, pH, rheology and colour), CP's effect on the organoleptic features of food has been found (Warne et al., 2021). Fresh-cut food quality is influenced by texture, nutritional content and look. The amount of CP therapy affects the colour of fresh vegetables and fruits. Studies on food products after CP treatment revealed that texture retention was achieved (Pankaj et al., 2018a). A sensory characteristic necessary for evaluating food quality is food flavour. It is affected during food processing by chemical reaction products (such as aromatic compounds) (Lacombe et al., 2015). The carotenoid pigments being broken down by plasma species may be a reason for the notable increase in the tomato's overall colour value that was noticed as treatment duration increased (Ali et al., 2021). It was observed that there were no noticeable colour changes when CP was applied to carrots, lettuce, cherries, apples, kiwifruit and strawberries (Ziuzina et al., 2016; Ramazzina et al., 2015; Niemira & Sites, 2008; Misra et al., 2014a, 2014b; Bermúdez-Aguirre et al., 2016; Farooq et al., 2023). Another blueberry study found that prolonged treatment times resulted in visible colour loss (Sarangapani et al., 2017a, 2017b, 2017c; Lacombe et al., 2015). Notable changes in the morphology of jujube slices were observed upon treatment with CP technology (Bao et al., 2021). When Asian saltwater bass fillets were treated with CP, it was observed that they developed unusual odours, which decreased their overall acceptability. One potential explanation for this could be the higher rate of lipid oxidation of plasma species (Olatunde et al., 2020). As reported in an investigation on dry-cured black carp, the primary by-products of CP, namely reactive oxygen and nitrogen species, improved flavour by speeding up the oxidation process of fatty acids (unsaturated). The process produces volatile flavour compounds, such as alcohols, aldehydes, and ketones (Ke et al., 2022). Studies reported that pre-treating samples with natural extracts (like coconut peel or chamuang leaf extract) before CP treatment can enhance their flavour (Zhang et al., 2022). Research on seabass slices revealed that CP treatment, combined with natural extracts, was superior to CP treatment alone (Olatunde et al., 2019). The CP application has demonstrated quantifiable reductions in organoleptic characteristics across various food categories. In fruit juices, dielectric barrier discharge cold plasma markedly enhanced the discoloration of tomato juice, as evidenced by an increase in the browning index from 2.35 to 4.54 with prolonged treatment duration, signifying carotenoid degradation that may diminish color and modify the perception of flavor (Starek-Wójcicka et al., 2023; Bayati et al., 2024). Similarly, ultrasound and two cold plasma methods, namely glow discharge and DBD were used to decrease astringency in cashew apple juice by lowering the tannin content and increasing the total phenolic content (Maia et al., 2025). The plasma discharge glow increased the glucose and fructose concentration by 51 and 46 %, respectively and DBD plasma reduced organic acids by up to 58 %. All in all, these non-thermal procedures enhanced the sweetness, flavor balance, and general acceptability of the juice through the optimal sugar to acid ratio. Similarly, DBD-CP technology was used to extend the shelf life of fresh-cut mangoes when stored under 25 °C of temperature (Liu et al., 2025). The treatment was shown to inhibit both browning and microbial growth, maintaining the appearance and firmness of the produce due to inhibition of the pectin methylesterase and polyphenol oxidase activities and activation of the peroxidase activity and thus the treatment has potential to preserve the quality of fresh-cut produce. On the same note, the pretreatment of CP is useful in enhancing the drying kinetics and quality of green peas. Bai et al. (2025) found CP altered the microstructure of the pea epidermis, decreasing the drying time by 18.18 % and rising the moisture diffusivity by 66.31. CP improved rehydration ratio, colour retention, total phenolic content and antioxidant activity under optimum conditions (90 s, 750 Hz, 70 % duty cycle) by 24.06 and 29.64, respectively. In dairy systems, CP exposure resulted in significant overall colour alterations; for instance, bovine milk processed under N_2 displayed an overall colour difference (ΔE) of approximately 1.9, a degree deemed perceptible to consumers, caused by protein oxidation alongside pigment alteration (Kowalska et al., 2022). Research on meat indicates color degradation and undesirable odors: in-package CP utilized on chicken breast at 70 kV for 3 min reduced redness (a*) by approximately 0.56 units along with yellowness (b*) by 0.91 units, while enhancing lightness (L*), resulting in raw meat that appears paler and not as fresh (Zhuang et al., 2024). In seafood, the application of CP has been correlated with reduced odour scores and the development of "peculiar" off-odours compared to untreated controls, attributed to the degradation of lipids and the generation of volatile aldehydes (Wu et al., 2024). Comprehensive analyses further substantiate that CP can increase total colour change (ΔE) and diminish sensory evaluations across various matrices, including coconut and dairy products (Bayati et al., 2024; Mundanat et al., 2025). These data demonstrate that, in the absence of optimal factor control, CP can adversely impact colour and flavour, two critical factors influencing customer approval.

5.2. *Effect on microbial activity*

Utilising novel technologies in the food industry has increased recently due to consumers' desire for fresh products and a healthier lifestyle, accompanied by an increase in food diversity (Ucar et al., 2021). However, with an increase in the consumption of low-processed or fresh foods, there is an increased risk of foodborne disease outbreaks. Microbial risk is considered when consuming unprocessed, non-heat-treated, or raw foods. To provide safe food and treat heat-sensitive food, another technique needs to be developed. Additionally, the applications of different forms of heat treatment have been investigated due to the need for non-thermal and high-quality food to minimise changes in food ingredients during processing and reduce microbiological contamination (Fernández et al., 2013). Using non-thermal plasma for bacterial inactivation is a complex process, and the action mechanism should be considered, as it is not entirely understood (Lu et al., 2014). Besides fungal inactivation, mycotoxin detoxification can be performed with CP (Laroque et al., 2022). During plasma treatment, microbial cells are primarily affected by cell contact and plasma ions. Reactive plasma species have been connected to the direct oxidative effect on the outermost part of microorganisms. The action of plasma is influenced by moisture; moist organisms exhibit more significant effects than dry ones. The cell damage is caused by the formation of DNA adducts from malondialdehyde upon plasma application (Thirumdas et al., 2015). Research has examined the effects of CP on immune *Bacillus, Geobacillus,* and *Penicillium* spores found on food and observed that *Bacillus coagulans (B. coagulans)* spores were 3-$\log_{10}$ inactivated after 10 s (Beyrer et al., 2020). According to a study, CP is used to inactivate bacterial processes by peroxidising the lipids in cell membranes. Furthermore, it has been noted that *E. coli* membrane permeability to propidium bromide and malondialdehyde rose in tandem with an increase in bacterial inactivation by plasma (Dolezalova & Lukes, 2015). Studies have reported that *B. coagulan* is inactivated at the highest rate at 7.1 W at 5 s, the fastest among these power intensities: 4.1, 5.7, and 7.1 W (Beyrer et al., 2020). A study found that at 30 kV and 5 min microbial load of black pepper reduced to 1.63 log CFU/mL after 1 h, but no additional significant reduction was detected at a period longer than 24 h but no additional significant reduction was detected at a period longer than 24 h (Charoux et al., 2020). All in all, the findings support the claim that increased voltage and treatment time are required for decontaminating microorganisms, especially vegetative cells. A study on Atlantic herring reported that a higher voltage (80 kV) was more effective in minimising microbial counts. In comparison, a lower voltage (70 kV) had a less adverse effect on key quality factors, such as colour modification and lipid oxidation (Albertos et al., 2019). According to a study, the longer and higher the power used to treat walnut kernels using electromagnetic low-pressure cold plasma (LPCP) at different powers, the better the microbial inactivation. The most significant reduction in the microbial population occurred at 50 W output and a treatment time of 20 min. The total viable count, mould, and coliform all exhibited log reductions of 1.09, 0.89, and 0.97 log CFU/g, respectively. Longer treatment duration is not desirable. However, a suitable increase in CP application length will boost microbial destruction efficiency preferably (Ahangari et al., 2021). A study demonstrated the effects of CP, UV-C and aqueous ozone (AO) on the blueberry's *Botrytis cinerea*. To preserve the blueberry's characteristics and boost its antioxidant activity during postharvest storage, all treatments can potentially damage the *Botrytis cinerea* cell membrane, releasing cytoplasm and nucleic acids. Compared to conventional sterilisation techniques (UV-C and AO), CP showed the lowest spore germination, the highest nucleic acid value and activity against the development of mycelial biomass. Because the UV penetration depth for UV-C can reach approximately one μm, whereas for the CP, it was 10 μm, UV-C was less effective at preventing the growth of *Botrytis cinerea* (Zhou et al., 2019). According to a study, cells may undergo physiological changes due to apoptosis and an increase in the accumulation of lipid bodies when the density of CP reactive species is insufficient to disrupt the spore structure (Panngom et al., 2014). A study examined the impact of CP on aflatoxin formation in peanuts infected with *Aspergillus flavus* and *Aspergillus parasiticus*. After administering 40 W for 15 min & 60 W for 12 min, they discovered that the amount of aflatoxin B1 had dropped by over 70 % and 90 %, respectively (Devi et al., 2017). Table 2 discusses the effect of different treatment methods on the microbial activity of fruits and vegetables. Likewise, DBD cold plasma had a high antifungal activity when tested against typical bread spoilage fungi (*Penicillium* spp., *Aspergillus niger*) with as high as 7-log reductions in fungal counts and fungicidal effects observed at higher intensities, which is of interest in preserving baked goods (Lemos et al., 2025). Hu et al. (2025) explained the antibacterial effect of ACP towards *Pseudomonas fluorescens* and *Pseudomonas putida* through which reactive species (ozone (O_3), hydrogen peroxide (H_2O_2), nitric oxide (NO)) formed in the course of treatment interrupted cell membranes, inactivated important dehydrogenases and damaged bacterial DNA, effectively prolonging the shelf life of shrimp paste.

CP is being investigated for its potential to disinfect refrigerated meats by inactivating pathogens such as L. *monocytogenes* and *S. typhimurium*, while preserving colour and sensory quality, and in certain studies, prolonging chilled shelf life. Both direct cold atmospheric plasma (CAP) and in-package plasma methods demonstrate effectiveness on raw and vacuum-packed meats, such as beef loin, with minimal thermal impact (Paulsen et al., 2022; Bauer et al., 2017; Misra et al., 2019a). Recent study has made a comparison between cyclical and one-time ACP in red shrimp in cold storage and identified that cyclical treatment was more effective in reducing the total viable counts and in inhibiting some of the most active spoilage bacteria like *Aliivibrio, Pseudoalteromonas* and *Psychrobacter*. Cyclical ACP treatment preserved protein integrity, minimized cooking loss and improved texture, sulfhydryl content and Ca^{2+}-ATPase activity by day 8 than single exposure. Such results indicate that streamlined cyclical ACP treatment would provide a better freshness and quality maintenance of seafood goods (Hu et al., 2025). In grains, CAP (encompassing dielectric-barrier discharge and remote/afterglow modes) may efficiently breakdown mycotoxins, including deoxynivalenol, aflatoxins and zearalenone on kernels with respect to largely maintaining quality; reported reductions vary from approximately 50 % DON in barley within min to significant decreases in AFB1/FMB1 in maize, with identified reaction products and kinetics aiding in safety assessment (Feizollahi et al., 2020; Lippolis et al., 2025; Zhang et al., 2023). Similarly, cold plasma as a non-thermal, chemical-free process was used for decontaminating the egg surface, which provides a possible alternative to the traditional egg-washing process. The best combination was 400 W power, 60 s exposure, 1 cm distance, and 35 L/min airflow at 65 % relative humidity which produced the maximum reductions of 1.94 log (98.74 %) with *E. coli* and 1.11 log (92.20 %) with *Salmonella enterica*, indicating the effectiveness of cold plasma in inactivating microorganisms on eggshells (Movasaghi et al., 2025). In addition to microbial control, oxidation of coconut globulin by ACP elucidated the oxidation mechanism of amino acids, and hydroxyl radicals were the key oxidants that acted on methionine, cysteine, and arginine residues, which was used to theoretically explain protein modifications (Chen et al., 2025). The commercialisation process is hindered by engineering constraints, including the optimisation of electrode materials and geometries, ensuring discharge uniformity in DBD systems, controlling humidity and gas composition, and developing continuous, high-throughput conveyors or in-package systems that provide consistent "doses" across diverse food products. Additionally, the absence of standardised reporting and metrics hinders comparability, validation, and regulatory approval (Ragni et al., 2016; Cullen et al., 2018; Alves et al., 2024; Pampoukis et al., 2025).

5.3. *Effect on protein*

The essential elements of food are proteins, which produce amino acids (AA) in the body. The human body has several structural and functional characteristics, including the capacity to hold oil and water, emulsification, and gel-like foaming (Foegeding, 2015). The study of ecology-friendly and efficient protein production addresses the need for alternative proteins, particularly those dominated by plant proteins. CP treatment can enhance the chemical and physical properties of plant proteins, promoting a sustainable pathway. Through the process of amino acid derivatisation, plasma-generated ROS interact with proteins. When the ROS are attacked by the proteins, the active sites are formed and more hydrophilic groups are produced (Basak & Annapure, 2022). The CP treatment can also alter protein complexes, affecting their primary, secondary, tertiary, and quaternary structures, thereby increasing their nutritional and functional characteristics (Kopuk et al., 2022). Segat et al. (2015) showed that processing isolated whey protein for 1 to 60 min at 70 kV significantly raises the carbonyl level in CP-treated materials. Modifications in the AA chain groups, mainly those that contain $-NH_2$ or peptide or -NH bonds, cause this. Nyaisaba et al. (2019) found that when the crude squid shell protease was heated at 60 kV in a DBD system for various treatment times, the carbonyl content improved and the free sulfhydryl groups decreased. Sharifian et al. (2019) demonstrated that the carbonyl group level of beef myofibril protein increased as the amount of DBD plasma was treated and the treatment length increased. As revealed in studies, ACP treatment altered the wheat flour's protein to a secondary structure, resulting in variations in its rheological characteristics. Additionally, dough strength can be enhanced by forming disulfide bonds (Misra et al., 2015). The same results were observed in another study. APC treatment changed the rheology of quinoa flour, which was probably caused by the polymerisation of the protein and the development of disulphide bonds through the plasma therapy (Zare et al., 2022). One study indicates the possibility of atmospheric plasma having effects on the rheology of the wheat flour dough. They claimed that the viscous and elastic moduli of strong wheat flour increased after plasma application. When CP was given to proteins, the quantity of beta sheets and alpha helices varied, changing the secondary structure of proteins (Misra et al., 2015). According to research by Pérez-Andrés et al. (2019), CP treatment could help achieve the required qualities of certain food products. In addition, it was discovered that DBD treatment could alter the amount of carbonyls in fish protein from 0.5 to 1.5 nmol/mg in baseline samples to 0.5 to 2.5 nmol/mg in plasma-treated samples. A study by Albertos et al. (2017) showed the effects of CP on fresh mackerel muscle protein and found that it decreases the myofibrillar circuits of immobilised water. A study investigated the physicochemical effects of CP on myofibrillar proteins extracted from white prawns (*Litopenaeus vannamei*). Due to precipitation, aggregation, and coagulation, the pH decreases from 6.77 ± 0.02 to 6.07 ± 0.02, and the protein solubility decreases. Meanwhile, the size of the particles increases due to changes in tertiary and secondary protein structures (da Silva Campelo et al., 2019). The compromising effects of CP are evident in proteins, resulting in alterations such as enzyme deactivation, modifications in hydrophilicity or hydrophobicity, changes in cooking properties, and improvements in functional qualities (Olatunde et al., 2023). The treatment of protein with plasma resulted in the detection of more pronounced aromatic, sulfur-containing and non-sulfur-containing amino acids due to the production of HO•. These radicals can sever peptide and disulfide bonds, altering the protein's structure and subsequently causing the oxidation of amino acids, particularly affecting aromatic amino acids like tryptophan (Bora et al., 2022). For instance, when chlorogenic acid undergoes CP treatment, reactive species may oxidize its hydroxyl groups, facilitating the generation of quinones or oligomerized products that may display modified or improved antioxidant capabilities (Shanker et al., 2023). Modifications to proteins by plasma encompass fragmentation, side chain alterations, backbone modifications, crosslinking and conformational changes (Dharini et al., 2023). Conversely, marination with a cold plasma-treated chlorogenic acid solution resulted in a reduction of carbonyl content to 1.35 nmol/mg, while the scavenging activity for DPPH free radicals and overall antioxidant capacity rose by 2.6-fold and 2.31-fold, respectively. Furthermore, the levels of heterocyclic amines, including polycyclic aromatic hydrocarbons, in the roasted beef were decreased (Yang et al., 2025a). Treatment with CP greatly altered the structural and functional characteristics of walnut protein isolate (WalPI) and unfolded the tertiary structure and changed the elements of secondary structure reduced a-helixes and increased b-sheet and random coil content. These structural changes not only increased fluorescence intensity, but also generated a crystalline and irregular microstructure of spheres. Functionally, CP treatment decreased particle size, enhanced solubility by 11.42 % and also significantly enhanced emulsification activity and stability (0.50 m^2/g and 1.22 mins respectively) (Deng et al., 2025) after 90s of CP exposure. In a separate method, the cold plasma-based treatment of soy protein isolate (SPI-CP) was introduced as an enhancement of enzymatic hydrolysis, where the proportion of hydrolysis was raised to 27.2 % and the extent of solubility was accumulated to 66.0 %. Less surface hydrophobicity and reduced particle size were also observed in SPI-CP to increase the dispersion stability. The structural analysis revealed that cold plasma caused unfolding of the primary structure of the protein to yield long peptide chains and enhanced functionality (Yang et al., 2025a). In addition, ultrasound-assisted cold plasma (UC) has demonstrated encouraging outcomes with the structure, functionality, and safety of peanut protein (PP) (Wang et al., 2025). UC 25 min caused a-helix to b-sheet rearrangements, decreased the fluorescence intensity of aromatic amino acids by 77 % and increased the hydrophobicity by 32.83 times, and emulsifying and foaming capacities by 102 and 63 % respectively. Notably, UC25 has interfered with allergenic epitopes and suppressed IgG binding by 74 % and shifted immune response; restoring the Th1/Th2 ratio to promote IFN-g release and inhibit IL-13 thereby, dramatically decreasing allergic symptoms and providing a platform to create hypoallergenic peanut-based products.

5.4. *Effect on carbohydrate*

Carbohydrates are one of the biopolymers most commonly used in various industries, such as pharmaceuticals, food, paper, textiles, and starch is a common type of carbohydrate. CP treatment is a valuable substitute for chemical modification of starch (Okyere et al., 2022). Carbohydrates are synthesised by plants to store energy (Jiang et al., 2022). Studies have reported that applying the DBD process to blueberries enhances their sugar content and can stabilise sugar levels at room temperature. Moreover, the length of CP treatment was associated with the time when the amount of sugar began to decrease (Dong & Yang, 2019). According to a study on orange juice, oligosaccharides broke down, fructose levels dropped, and sucrose levels climbed following the CP process (Almeida et al., 2015). According to a study, CP treatment of cashew apple juice eliminated all reducing carbohydrates, including glucose, fructose, and non-reducing sucrose (Rodríguez et al., 2017). Several studies have indicated that the time required to boil brown rice decreases, suggesting the presence of polar functional groups within the starch granules. Furthermore, they observed that the degree of gelatin formation increased after plasma processing (Thirumdas et al., 2016). A study examined the physicochemical, rheological, and structural properties of potato starch nanocrystals (SNCs) produced by the CP process. The shape and mode of SNC crystallisation were unaffected by CP treatment; however, it did reduce crystallinity. The swelling power, apparent viscosity, gelatinisation temperature and amylose content of SNCs all drop after the CP treatment; this could be because amylopectin branch chains depolymerise and SNC molecules break down (Shen et al., 2022). In one study, they discovered that treating rice starch with CP reduced the pasting temperature, gelatinisation temperature, amount of hydrolysis, amylose concentration and degradation tendency (Thirumdas et al., 2017). A study found that the increase in water binding sites and surface etching was due to reactive plasma species splitting down the protein and starch, which was the cause of the greater rate of water uptake in black gram (Sarangapani et al., 2017c).

The utilization of CP in food science has demonstrated minimal damage to the carbohydrate components of food (Shanker et al., 2023). The DBD treatment of maize starch was suggested to move toward more difficult-to-digest carbohydrate forms, as it decreased the readily digestible starch proportion from 56.47 % to 51.86 % while increasing the resistant starch content from 6.98 % to 9.08 % in cereal systems (Zhang et al., 2020). Taro starch subjected to high-voltage DBD plasma exhibited a significant reduction in amylose content (from 20.12 % to 15.98 %) and molecular depolymerization, as evidenced by a fall in weight-average molecular weight from 12.79×10^8 to 5.35×10^8 g/mol (Li et al., 2021). Wheat starch subjected to atmospheric plasma jets exhibited diminished pasting stability, as evidenced by a reduction in breakdown viscosity from 584 to 331 cP (−43.3 %) and a decrease in setback viscosity from 1267 to 1033 cP (−18.5 %), signifying compromised granule integrity and modified retrogradation characteristics (Xiang et al., 2022). The application of CP in liquid foods resulted in the degradation of reducing sugars, as evidenced by the decline in glucose and fructose levels in cashew apple juice, indicative of oxidative cleavage of saccharides by reactive oxygen and nitrogen species. Additionally, in certain instances, the breakdown products of sucrose further influenced variations in sugar makeup during storage (Pankaj et al., 2018a; Bayati et al., 2024). Recent researchers have shown that ultrasound and cold plasma technologies have the potential to improve the quality and functionality of plant-based foods. It was found that combined ultrasound and plasma pretreatments enhance the drying and textural properties of vacuum freeze-dried kiwifruit crisps (Yue et al., 2025). Specifically, Ultrasound with plasma-activated water had the best porous structure, crispness, low moisture content (4.85 %), and high rehydration ratio (288.03 %), although it retained the total sugars and phenolics well. On the same note, ACP has been used in quinoa grains to enhance nutritional value, as well as minimise the antinutritional value. The application of ACP at 60 kV, 10 min reduced saponin and phytic acid content significantly with preferred flavonoids and phenolics content and reduced lipid oxidation significantly (Arjmand et al., 2025). In general, both ultrasound-plasma hybrid and ACP treatments are promising to enhance the efficiency of drying of food, its texture, and nutritional value, but optimization should be performed to reduce the losses of antioxidants. Moreover, cold plasma at low-pressure had a great impact on the absorption of water, softness of grain, and anthocyanin content of the black glutinous rice by modifying surface microstructure without affecting nutritional quality (Panngom et al., 2025). CP treatment of fresh pistachios at both 5 and 8 kV using different gases (AR, N_2, O_2) led to significant reductions in microbial counts and weight loss as well as an increase in antioxidant activity, anthocyanin content, and enzymatic balance (reduced PPO and increased GPx activity) to prolong shelf life and marketability (Mollaei et al., 2025). Equally, CP use in the modification of hausa potato starch to 3D food printing showed that physicochemical and rheological properties were sensitive to the type of feed gas used (Akhila et al., 2025). The treatments of the starch crystallinity, gel strength and viscoelasticity were improved by the use of the argon and oxygen CP, which consequently led to high precision in the printing of the starch, as the argon CP-treated starch presented a high level of alignment with the CAD model. The data collectively indicate that CP can diminish important carbohydrate fractions, including accessible starches and simple sugars, while altering the structure of polysaccharides, potentially affecting both the nutritional value and functional aspects of foods.

5.5. *Effect on lipids*

Lipid oxidation is crucial in analysing food's shelf life, producing different types of primary and secondary products that adversely affect food quality (Farooq et al., 2023). It's a worrying problem with eating. In addition to having a detrimental effect on sample flavour, colour, shelf life, and nutritional value, it can also contribute to the development of cardiovascular diseases. Lipid oxidation is frequently quantified by thiobarbituric acid reactive substance (TBARS) and peroxide value (PV). The sample matrix type, the degree of unsaturation, and pro- or antioxidant chemicals are a few factors that affect the oxidation rate (Ghnimi et al., 2017). ROS, which aids in the destruction of germs, are generated by plasma treatment and include hydroxyl radicals, superoxide anions and hydrogen peroxide. Unfortunately, reactive species, primarily free radicals, can initiate lipid oxidation by abstracting hydrogen ions from lipid molecules (Shahidi & Zhong, 2010). Its applications remain under study, and new types of plasma-based sources of food are developed, but its impact on lipids is not recognised (Gavahian et al., 2018). Many studies have concluded that CP processing makes no significant difference on the oxidation of lipids in beef jerky (Kim et al., 2014), frozen and fresh (Choi et al., 2016) and raw pork (Ulbin-Figlewicz & Jarmoluk, 2016). A study shows that the oxidation of lipids was enhanced after 10 min of beef and pork fresh processing. Lipid oxidation was also shown to increase when pork loin was subjected to an oxygen-containing plasma gas (Jayasena et al., 2015). The intervention of CP is reportedly therapeutically distinct, as per a study. Hydrogen plasma may be used to create partially hydrogenated soybean oil without generating trans-fatty acids. CP techniques have demonstrated definite advantages over traditional hydrogenation methods, as they don't require a catalyst and can be carried out at atmospheric pressure and room temperature. Although this method appears to be a promising substitute for traditional catalytic hydrogenation, further research is needed to refine the treatment procedure and evaluate the capabilities of partially hydrogenated oil produced from CP (Yepez & Keener, 2016). A study reported that fresh mackerel fillets treated with CP exhibited significant oxidation of lipids. They discovered that dienes of hydroperoxides/kg lipid increased from 1.42 to 5.56 mmol, and PV increased from 6.89 to 37.57 meq. Active oxygen/kg lipids after plasma treatment for 5 min at 80 kV. It was also observed that a decrease in eicosapentaenoic acid (C20:5, n-3) and oleic acid (C18:1, n-9) occurred after plasma treatments (Albertos et al., 2017). A study claims that the Criegee mechanism oxidises lipids in CP. They also discovered that the typical products of oxidation in model meat and dairy fat matrices were aldehydes (nonenal, hexanal, nonanal, and pentenal), hydroperoxides (9- and 13-hydroperoxy-octadecadienoylglycerol species), ozonides and carboxylic acids (nonanoic acid, 9-oxononanoic acid and octanoic acid) (Sarangapani et al., 2017b). Studies on the effects of CP on the lipids in various dietary products are scarce. Nonetheless, published data suggest that plasma gas and treatment duration could be significant factors affecting the oxidation of lipids (Pankaj et al., 2018a, b).

Nonetheless, the appropriateness of CP for processing fatty foods, particularly those that are sensitive, as well as its potential to induce chemical alterations, has been scrutinized. CP produces free radicals that rapidly oxidise, resulting in an unpleasant fragrance and flavour (Sonawane & Patil, 2020). The created reactive species can trigger lipid peroxidation, resulting in the formation of primary oxidation products, such as hydroperoxides, as well as secondary oxidation products, including aldehydes and ketones. For example, in dairy and dairy products, these chemicals can adversely impact the sensory qualities of food, resulting in rancidity and undesirable odours (da Cruz et al., 2025). Alpha-tocopherol disintegration in hazelnuts was detected at 15 % during atmospheric cold plasma and 11.5 % during low-pressure cold plasma (Bayati et al., 2024). Furthermore, the data indicated a decrease in the fatty acid composition due to reactive oxygen species and ozone generated during processing, particularly in linoleic and linolenic acids, which are necessary fatty acids for human nutrition (Thirumdas, 2023). In a separate investigation, the linoleic acid content in pretreated tilapia fillets decreased by 3.02 % under one gas condition and by 2.58 % under another. In treated samples, polyunsaturated fatty acids (PUFAs) diminished by as much as 13.04 %, primarily due to oxidative degradation induced by ROS (Sang et al., 2024). Therefore, a low voltage (below 20 kV) is advised to mitigate these consequences (Ogundipe et al., 2024). Hu et al. (2022) indicated that in-encapsulation CP pre-treatment could markedly diminish the levels of polycyclic aromatic hydrocarbons in roasted steaks. CP is a low-temperature, atmospheric-pressure, environmentally friendly process for making partly hydrogenated oils (Shabbir et al., 2024). In contrast to traditional hydrogenation, CP does not require high pressures, high temperatures, or catalysts like nickel, which stops the production of toxic trans-fatty acids. Conventional hydrogenation techniques enhance oxidation and flavour stability by adding hydrogen to unsaturated fatty acids to transform oils into semi-solid or solid forms, however because of harsh processing conditions, they frequently result in trans fats. On the other hand, CP produces atomic hydrogen in the plasma, which selectively saturates double bonds at low temperatures and prevents trans-fatty acid synthesis (Wongjaikham et al., 2023).

6. Application of cold plasma

Several factors, including the global population expansion, have increased the demand for energy resources, water, and food, underscoring the need for sustainable and innovative technologies in the food and agriculture sectors. The potential of CP technology to provide long-lasting and innovative solutions is demonstrated by numerous instances of inactivating different microorganisms and enzymes, which have successfully mitigated various hazards across diverse industries. Food preservation with CP has been effectively demonstrated in several recent research studies (Table 1). Discusses the effect of different types of plasma on various foods. CP technologies can also be applied in food-related fields, such as desensitisation treatment and chemical structure modification (Jiang et al., 2022). The following section discusses a few uses for CP.

6.1. *Application in the dairy processing sector*

The dairy industry employs thermal methods, such as high-temperature-short-time (HTST), to ensure safety and preserve the shelf life of milk. The heating process can ensure milk safety, but prolonged, excessive heat treatment can degrade milk quality by generating protein

Table 1
Effect of different types of plasma on various foods.

S. no.	Food Material	Treatment	Source of Plasma	Observations	Refs.
1.	Pitaya freshly cut	Packaged sample for 5 min at 60 kV	DBD-ACP	At time 0 h phenolic content – 0.756 g/kg and antioxidant activity – 59.33 %. After 36 h at 15 °C phenolic content – 1.347 g/kg and antioxidant activity – 87.71 %	Li et al. (2019a, 2019b)
2.	Pear freshly cut	Packaged sample for 1 min at 65 kV	ACP	Quality characteristic asides organoleptic quality maintained while respiration was stopped Pectin methylestrase and peroxidase activities reduced	Zhang et al. (2021)
3.	Tomato Juice	10 kHz for 0–5 min	DBD	Increase in browning index from 2.35 to 4.54	Ali et al. (2021)
4.	Wheat Germ	24 kV for 25 min	DBD-ACP	Lipoxygenase and lipase activity reduced to 49.98 % and 25.03 % respectively	Tolouie et al. (2018)
5.	Brown Rice	15 kHz, 250 W, 5–20 min	DBD	Decreased hardness with an increase in α-amylase activity	Lee et al. (2016)
6.	Black Gram	40–50 W, 13.56 MHz for 5–10 min	RF Plasma	Surface hydrophillization with a decrease in moisture and ash content, cooking time and hardness	Sarangapani et al. (2017c)
7.	Milk	70 and 80 V for 120 s	DBD	Reduced activity of metabolic enzymes and bacterial cell membrane broken	Wu et al. (2021)
8.	Chicken fillets	70 W, 80 kV for 3 min	DBD	Decrease in yellowness and redness of meat with no effect on appearance of meat at storage (4 °C for 3 days)	Wang et al. (2018)
9.	Corn Kernel	500 W for 50 s	CP pre-treatment	Drying efficiency of corns increased while drying time reduced	Li et al. (2019c)
10.	Mackerel Fillets Fresh	50 Hz, 70–80 kV for 1–5 min	DBD	No major difference of TBARS value, pH, moisture content Higher eicosapentaenoic and oleic acid in treated sample	Albertos et al. (2017)

DBD: Dielectric Barrier Discharge; ACP: Atmospheric Cold Plasma; RF: Radio Frequency; CP: Cold Plasma; TBARS: Thiobarbituric acid reactive substance.

denaturation, flavour alterations, vitamin deficits and non-enzymatic browning. CP can swiftly and non-thermally pasteurize milk, maintaining its quality and ensuring food safety (Nikmaram & Keener, 2022). A study has shown that most tests conducted on milk and milk products have employed the DBD approach. In milk, a DBD technique (80 V-120 s) killed 100 % of *E. coli* and *Staphylococcus aureus (S. aureus)* and roughly 98 % of L. *monocytogenes*. Higher lipid peroxidation was also brought on by longer treatment times and higher voltages. The elevated lipid peroxidation, however, was similar to that of milk treated with Ultra high temperature (UHT) (Wu et al., 2021). UHT processing effectively sterilizes the milk or milk-derived beverages so that, when packaged under aseptic conditions, they should be resistant to spoilage for very long periods (years) (Anema, 2019). Another study found that treating milk with DBD at 2 kV and a lower pressure (0.16 bar) reduced the background microflora by approximately 1 logarithmic unit without negatively affecting the physicochemical characteristics (Manoharan et al., 2021). Numerous milk products, such as skim milk, sliced cheese, UHT milk and whole milk, have already undergone testing using CP. According to studies, CP may be a viable substitute for traditional milk processing methods, as it is less likely to affect the colour, pH, flavour, and nutritional content of milk products. In a matter of seconds, it also rendered the alkaline phosphatase enzyme and contaminating microbes inactive (Rathod et al., 2021; Song et al., 2009; Coutinho et al., 2018). According to another finding, DBD plasma sterilisation, which utilises a voltage of 3 kV for 3 min at a frequency of 500 Hz, effectively eliminates all the germs found in raw milk (Aslan, 2016). In a different investigation, the CP approach effectively inhibited mould growth in Kashar cheese. It has been noted that *Aspergillus favus* and *Penicillium crysogenum* can be effectively inactivated by applying CP with varying compositions of gases. According to reports, based on application time and gas composition, both mould types reduced the growth of the other by 3–4 logs CFU/cm^2, thereby enhancing the storage stability and textural qualities of Kashar cheese (Akarca et al., 2023). In a study by Nemati and Guimarães (2024) dielectric barrier discharge cold atmospheric plasma (DBD-CAP) treatment showed good results in preserving the physicochemical and sensory properties of mozzarella cheese. 3 min treatment significantly preserved moisture, fat, protein content while inhibiting the yeast growth and shelf life extension by least two days without adverse quality changes. Similarly, treatment by cold plasma conditions (3–4 min) at 10 kHz and 20 kV temperature has proven to drastically improve the sheep milk protein functionality such as water-holding capacity, solubility, foaming stability, and phosphorylation (Zhang et al., 2024). In a similar manner, raw bovine colostrum underwent different ACP discharges of 15 kV in 20 min produced approximately 98 % microbial inactivation by reducing total plate and coliform counts by 1.41 and 3.55 log CFU/mL, respectively, without significant pH variation (Ravash et al., 2025). All in all, the findings proving the efficacy of CP in terms of a safe and efficient non-thermal preservation technique of dairy products.

6.2. *Application in food packaging*

Food packaging materials shield food items from the external environment during handling, distribution and transit. CP is used to decontaminate packing material externally because it flows all over the surface, reducing the chances of a shadow effect (Thirumdas et al., 2015). According to a study, the plasma-treated surface may exhibit chemical and physical alterations. The primary physical alteration brought about by plasma's intense bombardment of particles on the surface of the polymer is an increase in surface roughness. Additionally, the chemical bonding of reactive species to polymer chains can occur, altering the chemical composition of the surface or secondary bonds (Pankaj & Thomas, 2016). According to a study, areas with higher porosity age more quickly than those with intermediate porosity, and the hydrophilicity of polymers naturally declines with age (Vesel et al., 2020). As observed in a study, hydrophilicity is increased by treating polyamides (PA) with PJ-ACP in an argon (Ar) environment, as this increases the surface's polar component free energy. Following a 20-second treatment, the PA contact angles decreased from 51.3° to 15.0° for water and from 47.4° to 24.0 According to a study, after a 10 min PJ

Table 2
Effect of various types of plasma treatment on microorganisms in fruits and vegetables.

Sl. No	Food Material	Treatment	Source of Plasma	Microbial Observations	Refs.
1.	Sundried Tomatoes	6 kV for 5 - 30 min, 23 kHz	DBD	Filamentous fungi and total mesophilic content significantly reduced	Molina-Hernandez et al. (2022)
2.	Radish Sprouts	50–1000 W, 2.45 GHz	Microwave generated Plasma	2.6 ± 0.4 log$_{10}$ CFU/g reduction of *S. typhimurium*	Oh et al. (2017)
3.	Leafy vegetables fresh	2500 Hz, 26 kV	DBD	Microbial log inhibition of 5.5×10^3 CFU/mL of *E. coli*	Shah et al. (2019)
4.	Carrots freshly cut	60 Hz, 100 kV for 120 s	DBD-ACP	Reduction of yeast, aerobic mesophiles and molds nearly 2 log$_{10}$ CFU/mL	Mahnot et al. (2020)
5.	Tomato	15 and 60 kV, for 5, 10, 15 and 30 min, 50 Hz	ACP	Log reduction highest of 6 log$_{10}$ CFU/mL of *E. coli*	Prasad et al. (2017)
6.	White Grape Juice	80 kV for 4 min	HVACP	Reduction of *Saccharomyces cerevisiae* by nearly 7 log$_{10}$ CFU/mL Total Flavonols increase after treatment	Dong and Yang (2019)
7.	Orange Juice	90 kV for 30–120 s	DBD	Reduction in *Salmonella enterica* nearly 5 log$_{10}$ CFU/mL	Xu et al. (2017)
8.	Mandarins	27 kV for 2 min	DBD	Decrease in *Penicillium digitatum* disease	Bang et al. (2020)
9.	Bulk Romain Lettuce	42.6 kV, 0 and 2400 Hz for 10 min	DBD	Reduction in *E. coli* count to 1.10 log$_{10}$ CFU/g	Min et al. (2016)
10.	Apple Juice	1.1 MHz, 65 V	Plasma Jet	5 log$_{10}$ reduction of *Citrobacter freundii*	Surowsky et al. (2014)

DBD: Dielectric Barrier Discharge; ACP: Atmospheric Cold Plasma; HVACP: High Voltage Atmospheric Cold Plasma.

Table 3
Comparison of different plasma sources.

Sl. No	Plasma Source	Electron Temp. (eV)	Gas Temp. (K)	Typical Applications	Refs.
1.	Dielectric Barrier Discharge	1 - 5	300 - 1000	Food decontamination, sterilization, surface modification	Misra et al. (2016b); Shintani et al. (2010)
2.	Plasma Jet	1 - 10	300 – 1500	Biomedical sterilization, wound healing, food preservation	Lu et al. (2016); Misra et al. (2019a)
3.	Corona Discharge	1 - 5	300 - 600	Ozone generation, pollution control, food surface control	Fridman (2008), Misra et al. (2011)
4.	Gliding Arc	1 - 5	2000 - 5000	Gas conversion, plasma chemistry, pollutant removal	Fridman (2008), Starikovskaia (2014)
5.	Microwave Plasma	1 - 3	300 - 2000	Semiconductor processing, plasma chemistry, thin films	Tendero et al. (2006)
6.	Plasma Activated Water (PAW)	1 - 5 (parent plasma)	~ 300	Antimicrobial, seed germination, food washing	Thirumdas et al. (2018), Ma et al. (2015)

treatment, biofilms *S. typhimurium, E. coli* and L. *monocytogenes* on collagen casing, PET and polypropylene surfaces showed a 3–4 log CFU/cm^2 (Kim et al., 2015). In one investigation, vacuum-packaged beef loins using sheets made of polyamide and polyethene were subjected to atmospheric-pressure CP. The treatment method reduced the counts of L. *monocytogenes, E. coli* and *S. aureus* on films by over two log units without compromising the integrity of the vacuum packing matrix. Moreover, a delay of 10 days was observed in oxidation (Bauer et al., 2017). Likewise, DBD treatment was employed on bilayer nanocomposite film of poly lactic acid-chitosan-zinc oxide to increase adhesion between the layers for better performance. However, plasma treatment minimized the water contact angle by 98.2° to 42.6° and the surface roughness was maximized by 19.75 to 31.5 nm. The optimally plasma-treated poly lactic acid showed an 80 % increase in tensile strength, while the bilayer film exhibited improved water vapor permeability of 0.64×10^7 g/m.h.Pa (Norozi et al., 2025). In another work by Tahmouzi et al. (2025) a biodegradable gelatin-sodium alginate (GSA) film loaded with silver nanoparticles (AgNPs) underwent cold plasma DBD treatment to improve the performance of films to give compact, structurally stable films, with better barrier properties and antibacterial effects against *E. coli* and *S. typhimurium*. Furthermore, the packaged samples with cold plasma-treated optimal films were lower in thiobarbituric acid (0.54 mg MDA/kg sample), total volatile nitrogen (19.04 mg/100 g), and total mesophilic bacteria count (5.8 log CFU/g) compared to other samples. In another study, atmospheric DBD cold plasma has effectively enhanced the quality and shelf life of apples up to 41 days by reducing the polyphenol oxidase and phenylalanine ammonia-lyase activities while preserving the activity of peroxidase, firmness and red coloration in the apples. In addition, the novel cold plasma decontamination method was more effective in reducing the pesticides (Malathion, chlorpyrifos and Fenthion) from the apple surfaces than the conventional methods (Sreelakshmi et al., 2024).

6.3. *Application in agrochemical residues*

The majority of pesticides included in agricultural products include dichlorvos, diazinon, omethoate, chlorpyrifos, parathion, cypermethrin, paraoxon, cyprodinil, fludioxonil and azoxystrobin. Both human health and the environment are endangered by the residue of pesticides in food. Accordingly, CP can reduce these substances (Mousavi et al., 2017). To eliminate insects, modern agriculture employs insecticides to reduce crop losses and control crop infestations. A study demonstrated how discharge plasma technology might remove organophosphorus pesticide residue from wolfberry surfaces. Accordingly, the study found that the applied voltage and treatment duration affected the removal of pesticide residues in healthy plasma (Zhou et al., 2018). A study found that gliding arc discharge plasma effectively removed pesticide residues from mango surfaces. They also investigated how this plasma therapy affected a few mango qualitative attributes. Cypermethrin and chlorpyrifos levels were successfully lowered by 63 % and 74 %, respectively, after 5 min of plasma treatment with argon carrier gas (Phan et al., 2018). A study found that after plasma treatment at 80 kV for 5 min, residues of pesticides on blueberries decomposed well, with degradation efficiency of 80 % for imidacloprid and 75 % for boscalid. The evaluated quality attributes demonstrated the necessary adjustments for the treatment environment. These observations indicate that CP treatment for 5 min at 60 kV and 60 s at 80 kV can preserve the nutritional qualities of blueberries (Sarangapani et al., 2017a). According to a study, the frequency and gas flow rate impact the plasma's ability to degrade pesticides. Chemical bonds are broken, and the flow rate increases when the frequency rises due to an increase in active species and average energy. The collaborative impact of the number of reactive species, mean energy and residence time in the discharge zone must be considered (Feng et al., 2019). Tropomyosin's allergic reaction to fresh king prawns (*L. vannamei*) was subjected to a plasma jet of cold Ar, which was investigated. Following a 15 min plasma treatment, IgG and IgE binding capabilities decreased by 26.87 % and 17.6 %, respectively. Additionally, after more than 9 min of treatment, surface hydrophobicity and total free sulfhydryl group concentrations changed (Ekezie et al., 2019).

6.4. Application in effluent treatment

Because water from the food industry contains a high proportion of organic loads, disposing of it is a significant problem. Wastewater can be treated using different chemical, thermal and filtration methods (Filipić et al., 2020). According to one study, CP (Cellular Polymers) and ROS have been shown to alter how liquid waste breaks down or decomposes quickly. Through electrohydraulic cavitation, UV photons generated during CP treatment indirectly provide pyrolytic action (Chaitradeepa et al., 2023). According to a study, industrial waste from tomato processing plants was treated with plasma jet exposure at 25 kV for 150 s, and wastewater from blackberries and beetroot showed a significant decrease in bacterial counts after 180 s. Additionally, plasma decreased the waste water's endotoxin compounds and *E. coli* levels by up to 90.22 % (Mohamed et al., 2016; Sarangapani et al., 2016). Jiang et al. (2014) and Marotta et al. (2012) have reviewed recent studies on non-thermal plasma for the mineralisation of pollutants using several catalysts, the breakdown of pharmaceuticals and pesticides, and the oxidation of products in phenols, water, and organic colours.

7. Limitations and potential risks associated with cold plasma (CP) technologies

CP technology has demonstrated significant potential in various fields, including sterilisation, surface modification, and even agriculture. However, there are a lot of limitations and in this paper we discuss these issues in detail and also suggest the possible solutions to enhance the efficiency of the system and its application.

7.1. Energy consumption

The first challenge is that energy consumption in the creation of CP requires a lot of energy and this may immensely discourage its larger adoption. This is done by the ionisation of gas molecules, which needs high power input, which has been supplied by renewable energy sources (Zhou & Liu, 2025). Developing an advanced power supply that is energy efficient can reduce the usage significantly. The use of pulsed power supplies instead of continuous-wave supplies can possibly enhance energy efficiency in the sense that it can supply energy in controlled bursts, hence reducing the total usage (Nakamura et al., 2023). The energy to generate the plasma can be lowered by the use of gas mixes which have a higher ionisation potential. Adding noble gases such as helium or argon may decrease the ionisation threshold, thereby decreasing requirements of energy. Using powerful control mechanisms that properly regulate the plasma parameters, such as the voltage, frequency and gas supply, will allow maintaining optimal conditions with minimal energy expenditure (Martinez-Montejano et al., 2019).

7.2. Key engineering hurdles for scaling up cold plasma (CP)

The improvement of CP systems in industries presents significant engineering challenges. Large systems should also be able to offer the homogeneous plasma dispersion in addition to consistent functionality which is not easy to achieve. The solution to scaling problems could be the development of modular plasma technologies that can easily be scaled by adding further units. The modules will act independently as each will enable the uniform production of plasma across large fields (Misra et al., 2024). Reliability in dispersion of the plasma may be supported by the application of technology, including multi-electrode systems and advanced designs of reactors (Thomas & Stapelmann, 2024). DBD reactors can be set to have multiple electrodes to achieve a homogenous distribution of the plasma. Scalability can be improved by developing high-throughput systems that are able to be able to process larger amounts of materials simultaneously. It involves adjusting the geometry of reactors and the dynamics of gas flow to ensure performance improvement (Yu et al., 2025). Implementation of CP technology requires investments in equipment, process optimisation and personnel training. The cost of adopted technology can be a challenge to its common use by small and medium-sized food producers. The design of equipment and scale of production might be limiting to implement the CP treatment of large-scale food production (Gavahian, 2024). Studies need to focus on an economic analysis to take into account capital and operating costs, the efficiency of run times, energy use and the cost of maintenance. Optimisation and improvement of design parameters of different methodologies will help in the process of transferring the lab and pilot-level test systems into large-scale industrial applications. Artificial intelligence, together with mathematical models can help to optimize processing parameters and guide regulatory rules.

7.3. Long-term stability

The reliability of the CP system is vital to its dependability and its practical use, which can only be achieved by ensuring its long-term stability. Stability can be affected by the electrode degradation, gas pollution, and wear of the components. The durability of the plasma systems can be enhanced with the help of high-performance materials that resist wear and deterioration (Sasikumar et al., 2025). Some of the materials used as electrodes such as tungsten or applied with implementing layers can withstand harsh plasma conditions. Regular maintenance programs and real-time monitoring systems could be used to help detect and overcome problems before they affect the functioning of the systems (Antony Jose et al., 2025; Dou et al., 2018). Sensors and diagnostic tools are potentially providing key data about the integrity of the system enabling proactive maintenance. Research and development of self-healing materials which would be capable of repairing small defects by themselves can significantly contribute to the stability of the plasma system over the long term. The materials will be able to fix surface fissures or wear, thus extending the lifespan of the device (Sasikumar et al., 2025). Next, the high cost of the manufacturing equipment of plasma as well as the need to have a special infrastructure can prevent mass adoption. Treatment times ranging between 20 s and 30 min have been reported in the literature, which can be used in industrial practice; nevertheless, shorter time can also be used (Sarangapani et al., 2019; Misra et al., 2019b; Lee et al., 2016; Domonkos et al., 2021). Additionally, manufacturers are not likely to make a massive change to the existing production line in adopting new technology and therefore this should be taken into account when building the system. Treatment of in-package CP can be affected by the food product depending on the food product composition and characteristics. Surface topography, moisture content, and fat content are a few of the parameters that might have an effect on the efficacy of CP treatment. The optimization can be demanded of certain types of food (Mollakhalili-Meybodi et al., 2021; Shanker and Rana, 2025).

7.4. Regulatory challenges for cold plasma (CP)

In-package CP application in the food technology processing requires regulatory authorisation. Food manufacturers are required to follow food safety laws and demonstrate the effectiveness and safety of the CP treatment to the regulatory agencies, which might take a long and complicated process. Overall, even in the regions where the CP technology has the potential to be effective, specific applications might not yet have the full regulatory approval (Bourke et al., 2018; Yepez et al., 2022). This will have an impact on its acceptance and marketing in the food industry. The production of reactive species, such as free radicals, is part of the use of CP, and that may harm human health in situations where it is not controlled properly. It is important to make sure that food products that have gone through the processing are safe and reduce possible hazards that may be connected with chemical residues or byproducts (Varilla et al., 2020). Another problem is the acceptance and perception of customer towards plasma-processed foods. The irradiation laws focus on setting proper levels of the dosage to control the food infection and at the same time reduce any negative effects on food quality (Olawoye & Popoola-Akinola, 2025). CP technology is controlled in order to ensure that it can be safely used in different industries, and when properly used, was found to be effective in disinfecting food products with little health-related risks (Alaguthevar et al., 2024).

7.5. Production of harmful substances

CP therapy can lead to production of chemicals that are potentially harmful. Reactive species containing nitrogen might react with organic compounds to form nitrosamines that are known to be oncogenic (Zhang et al., 2025). These species form the basis of antibacterial activity of CP, which effectively counter the viruses, fungi and bacteria by degrading cell walls and interfering with cellular processes. These reactions of these reactive species with food substances can lead to the formation of secondary by-products. Food reactive species can facilitate the production of acryamide, a chemical that is subject to potential health hazards, including reducing sugars and amino acids (Ravash et al., 2024). In an attempt to eliminate these undesirable effects, however, modification upon the variables of CP treatment, such as the type of gas involved, duration and intensity of exposure are necessary. Scientists are investigating the processes through which the reactive species react with food constituents to improve the knowledge and control of the undesirable production of by-products (Sasikumar et al., 2025). CP treatment has the ability to reduce microbial load and enhance food safety even though it may not contribute to significant extension of shelf life. More factors like temperature control, optimal packing and storage facilities should also be taken into consideration to attain the desired shelf life extension. It is also worth investigating methods to combine various non-thermal technologies, including in-package plasma, in keeping with the hurdle concept (Boateng, 2022; Noor et al., 2019). CP methods usually involve the application of gases which contain nitrogen and argon (Gavahian & Khaneghah, 2020). There is a threat of gas leaking, which may cause the replacement of oxygen in the immediate environment. It can be dangerous to individuals, since excessive oxygen could be thrown out and cause asphyxiation. Gas should be properly managed and supervised as well as have adequate ventilation to avoid such incidences. The treatment process may also result in certain by-products of CP systems, such as reactive oxygen and nitrogen species (Gavahian & Khaneghah, 2020). Such by-products can possess antibacterial properties, which in case of inadequate control mechanisms can result in food contamination. CP is generally a source of ultraviolet light, which can harm an individual eye and skin (Niemira, 2012).

8. Conclusion

Cold plasma (CP) treatment is an alternative promising method of food improvement in terms of quality and safety. CP was discovered to be useful improving the shelf life of various food products such as fresh fruits, dairy products, meat and sea food. High efficacy of CP is attributed to the fact that it removes a wide variety of bacteria at low temperatures thus maintaining the functional, nutritional, and sensory qualities of food products. Under optimal conditions of CP treatment, this process allows the slightest changes of vitamins, proteins and antioxidants. CP is highly favoured in the food industry since it's a non-thermal processing method that's particularly effective in microbial inactivation, food preservation, and food processing, among other areas. This method will make raw, less processed foods with longer shelf lives available on the market. Alongside the anticipated enhancements, concerns arise over the safety and risks of the procedure, and negative consequences may result from this approach. The negative impacts, such as scalability and standardisation of treatment regimens, as well as potential oxidative effects on lipids or pigments in certain meals, need to be considered. The food research community is continually seeking to develop methods that make food safer for people, thereby preventing such risks. Therefore, cold plasma treatment demonstrates significant potential as a safe and effective method for enhancing food quality and safety.

Declarations

Human and animal rights and informed consent

This article does not include any experiments with human or animal subjects done by the authors.

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CRediT authorship contribution statement

Rohit Kumar Gupta: Writing – review & editing, Visualization, Software, Resources, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Rafeeya Shams:** Writing – review & editing, Visualization, Software, Resources, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft. **Adity Bahndral:** Writing – review & editing, Visualization, Software, Resources, Data curation, Investigation, Methodology, Validation, Writing – original draft. **Kshirod Kumar Dash:** Writing – review & editing, Visualization, Software, Resources, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft. **Prashant Anil Pawase:** Writing – review & editing, Visualization, Software, Resources, Data curation, Formal analysis, Methodology, Validation. **Ayaz Mukarram shaikh:** Writing – review & editing, Visualization, Validation, Software, Resources, Investigation, Formal analysis. **Kovács Béla:** Writing – review & editing, Visualization, Software, Resources, Funding acquisition, Project administration, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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