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COLD PLASMA TECHNOLOGY FOR FOOD STERILIZATION: ADVANCES, MECHANISMS, AND FUTURE PROSPECTS IN ENSURING FOOD SAFETY

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Abstract

Cold plasma technology has appeared as one of the most advanced non-thermal food processing techniques for achieving effective sterilization without compromising food quality. As consumers increasingly demand fresh, slightly processed, and chemical free food, traditional sterilization techniques such as thermal pasteurization, chemical sanitizers, and irradiation have faced limitations due to nutrient loss, undesirable sensory changes and safety concerns. Cold plasma provides ahigh efficient, environmentally friendly and rapid method food microbial inactivation using reactive species, ions, electrons, UV photons and charged particles produced from ionized gas. This review paper aims to provide an extensive and updated overview of cold plasma principles, mechanisms of microbial deactivation, equipment used, effects on food quality, application across various food categories advantages, limitation and industrial prospects. The growing research interest and commercialization potential show that cold plasma could become an essential part of sustainable food preservation system in the near future.

INTRODUCTION

Food preservation techniques have been used for many centuries and have continuously evolved over time with advancements in knowledge and technology. Ancient people used different method to save agriculture product like sorting, grading, sun drying, salting and fermentation (Nwabor et al., 2022). As the population grows, the demand for food is also increase because it is basic need. For this reason, the importance of food safety has also grown and has become essential. Food availability and accessibility " Is a situation when all the people all the time have physical and economic access to sufficient save and nutritious food to meet their dietary needs for an active and healthy life" (FAO/WHO 2005).

Food safety according to the European union, is the condition in which food is safeguarded against different hazards that can be physical, chemical and microbial hazards occurring during various stages from processing to storage and distribution, ensuring that its quality and nutritional value remain suitable for human and animal consumption. It is important that a balance must be maintained between the protection of safe food and the protection of public health. The safety of food is the basic challenge, Ensuring the safety and reliability of food has become increasingly challenging, because growing demand, limited supply, and widespread food adulteration and fraud put pressure on the system (Gunarathne et al., 2022).

The EU's "farm to fork" concept aims to enhance food security by making the entire food chain from production to consumption safe, efficient and environmentally sustainable (Misra et al., 2016). Thermal treatment is the most benefit treatment of food. In Pakistan, Punjab standards and quality, Punjab and control authority (PSQCA), Punjab food authority (PFA) because to kill the pathogenic organisms and increase the shelf life of food. If we compare thermal treatment of Pakistan with EU, the treatment of EU is best due to strict standard and monitoring mechanisms. Despite technological advancements, thermal treatment is the most save and reliable method for ensuring the high quality of food in the European Union (Kim et al., 2016). Non-thermal method is another type of food safety in which they kill the harmful bacteria, and increase the shelf life of food without rely high temperature. The techniques used in non-thermal method like Pulsed electric fields, Cold plasma, Irradiation and Ultra violet rays uses exceedingly high pressure to inactivate bacteria and enzyme In this way they maintain food natural colour, flavour, reduce the need for chemical preservatives (Singh et al., 2022).

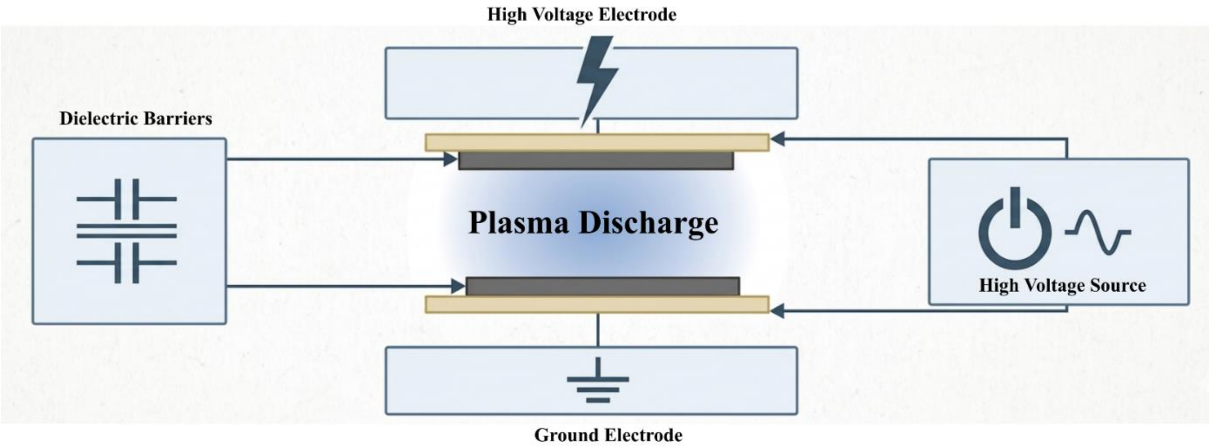
Effect of temperature changes

To decrease the impact of extreme ambient temperature stress in food industry use controlled heating method like LLT and HTST to decrease harmful microbes and keep food safe (Charoux et al., 2021). Cold temperature failure means when perishable food is not kept at their safe temperature especially during storage and transport. If cold chain is not maintained properly, so food can spoil quickly and bacteria can grow rapidly, increase the risk of food borne illnesses. To address this problem, use of modern preservation techniques like cold plasma, which consume low energy and safely eliminate microorganisms without producing harmful residues. In this way, proper cold chain management and controlled preservation methods help maintain both food safety and quality (Rao et al., 2023). This review paper explores the advancement and current application of CP in industry aimed at enhancing the product quality. Benefit of CP in food products, while discussing the potential opportunities for further innovation and optimization in food processing methods.

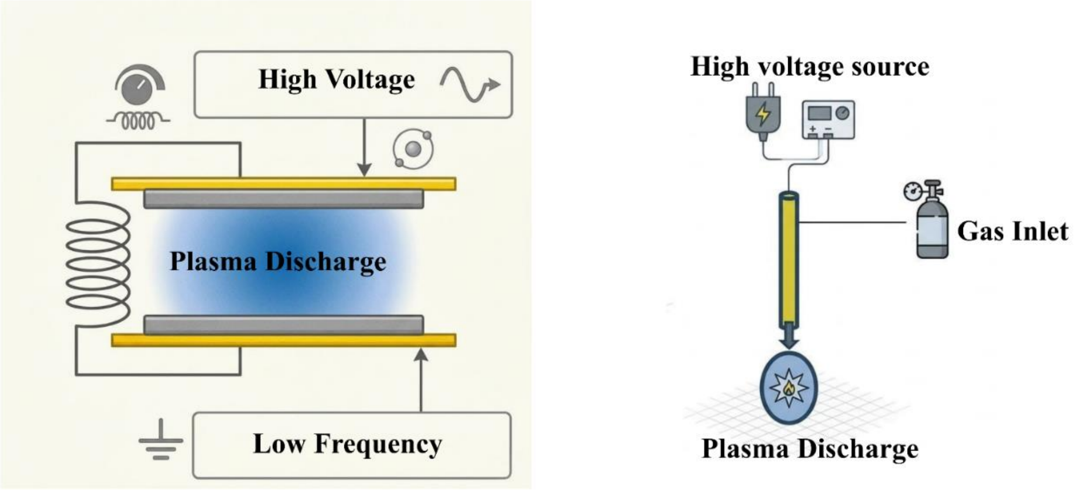
Principle and concept of cold plasma

Cold plasma is a non-thermal technology that operates near atmospheric pressure, which distinguishes it from other plasma-based techniques (Jayasena et al., 2023). Plasma can be produced through various energy sources that has ability to ionize gases, such as heat, light, radiation and high-energy waves. Each of these energy forms can supply enough power to remove electron from gas molecules and create an ionized state. However, in practical and industrial applications, cold plasma is most commonly formed by applying electrical or electromagnetic fields, as these methods allow better control and efficiency during plasma generation. (Pankaj et al., 2016). Its unique characteristics come from two main processes: Ionization and recombination. During ionization gas molecules particularly split into electron and positive ion. Subsequent, recombination occur when these electron re-associate ions, releasing energy as heat, chemical transformations and light which sustain the plasma environment (Boulos et al., 2023).

Ionization mainly occurs through electron collisions when electrons possess energy greater than the ionization threshold. It can be also done by photoionization or due to collisions between heavy particles, In photoionization an atom of neutral charge interacts with a high energy photon. Ionization is the fundamental process responsible for the formation of cold plasma, leads to the production of ROS and RNS i.e. reactive oxygen species and reactive nitrogen specie, respectively. These reactive species inactivate or sterilize microorganisms in food and can also modified surfaces. Recombination happens when high-energy electrons join positive ion again, forming neutral molecules. It releases energy in the form of heat, light or chemical energy. These neutral and excited molecules then create cold plasma. Disrupting microbial cell membranes is considered one of the important application of cold plasma (Aparajhitha et al., 2019). The cytoplasmic membrane acts as a barrier, protecting cells from external threats (Aparajhitha et al., 2019). The cold plasma technique generate the reactive oxygen species that trigger oxidative reaction that damage these membranes. During plasma treatment gas molecules such as oxygen, nitrogen and argon are ionized, forming ROS atomic oxygen (O), OH radicals, ozone, and reactive species of nitrogen including nitrogen oxide, and nitrogen dioxide (Rehman et al., 2016). The cold plasma system is generally classified into three main approaches; electrode contact, direct exposure and remote exposure. In the remote exposure method, the food is positioned at a distance from the plasma source. Reactive species generated in the surrounding air then interact with the food, leading to sterilization and chemical modifications. The direct exposure method places the food directly in contact with the active plasma region, where both short-lived and long-lived reactive species are produced and act on the food. In the electrode contact approach, the food is placed on or near the electrode generating the plasma, resulting in ion bombardment and emission of reactive chemical species. Additionally, cold plasma is widely employed for surface modification of materials, which is efficient and cost effective. In the food sector this method is particularly useful because it is challenging to create granular or powdered products that simultaneously maintain bulk properties while allowing targeted surface treatment. The plasma treatment induces surface phenomena, such as etching and sputtering, which enhance surface functionality and techno-functional properties of the material without altering its overall bulk characteristics (Fricke et al., 2012).



Dielectric Barrier Discharge DBD



Inductively coupled plasma

Figure 1: Schematic representation of major cold plasma generation techniques.

Cold plasma sources

Several plasma-generation methods are widely used in food processing applications. These methods include Dielectric barrier discharge, Corona discharge, gliding arc discharge, micro hollow cathode discharge, radio frequency, and microwave plasma. (Bermudez-Aguirre., 2020).

Dielectric Barrier Discharge (DBD)

This refers to form of electrical discharge where an insulating material like glass, quartz, or ceramic is positioned between two electrodes. This barrier helps control the discharge and allows the generation of non-thermal plasma. With the application of high voltage, the dielectric barrier prevents the formation of a continuous arc and instead produces many small electric discharges. This process maintains a low operating temperature; therefore, DBD is commonly used to generate non-thermal or cold plasma. In DBD systems, the dielectric layer blocks the direct flow of electric current between the electrodes, resulting in a stable and uniform discharge. This characteristic makes DBD particularly suitable for applications such as surface decontamination, food sanitation, packaging sterilization, reduction of toxic fungal compounds (mycotoxins), and enzyme inactivation (Nwabor et al., 2022).

Corona Discharge Plasma

High voltage leads to the production of Corona discharge plasma, and is typically applied in non-uniform media. Strong electric field around a pointed electrode causes the electrons to ionize in nearby molecules of gas or atoms (Mehta et al., 2022). The production of photons, electric fields, charge particles, glow discharge, streamer discharge, radicals and other reactive species leads to generation of this type of plasma. Because the discharge region is fhighly reactive and concentrated, food processing the treatment is generally performed beyond the high-voltage gap instead of occurring in between the electrodes. In certain configurations, a grounded screen is positioned between the food and the electrodes. This screen permits the passage of neutral particles and the most of the electric field (Fernandes et al., 2025). This method of generating plasma is simple, cost-effective and can applied in many industries for surface sterilization, microbial inactivation, electro-precipitation and more. However, its use in generally restricted to small, non-uniform areas, which limits its scalability for bulk processing (Birania et al., 2022).

Plasma jet

The plasma jet system consists of followings: a tube consisting of gas line in which electrodes are present, and the plasma jet is generated within this gas tube. Two main configurations are commonly used: one employs two electrodes with different positions for the mechanical and grounded electrodes, and another one consists of one electrode, which can operate in presence of precursor or without it. To generate the plasma jet, insert gases including argon and helium are generally used, which are specified as flow rate of gas. Various power source is employed to produce the plasma jet, including alternating current with high voltage, direct current with high voltage, radio frequency or microwave. A glass tube used by Alavi et al. with outer diameter of 4.6 mm and 2.0 mm inner diameter and copper strips having 0.1 mm thickness and 15 mm width as electrodes. The powered and grounded electrodes are of copper strips that are wrapped around the glass tube (Alavi et al., 2020).

Type of Cold Plasma Used in Food Sterilization

Cold plasma (CP) systems have been extensively studied for various applications throughout different stages of food processing. These applications cover the handling of raw materials and finished food commodities, and its application also includes disinfecting of machinery in processing plants and the nearby setting, due to the many advantages of this technology. The main benefits of cold plasma include operation at low temperature, short treatment durations, efficient energy use, and strong antibacterial effectiveness with minimal impact on food quality and environment (Bourk et al., 2017). Some applications of cold plasma in food and agriculture are given in Figure 2:

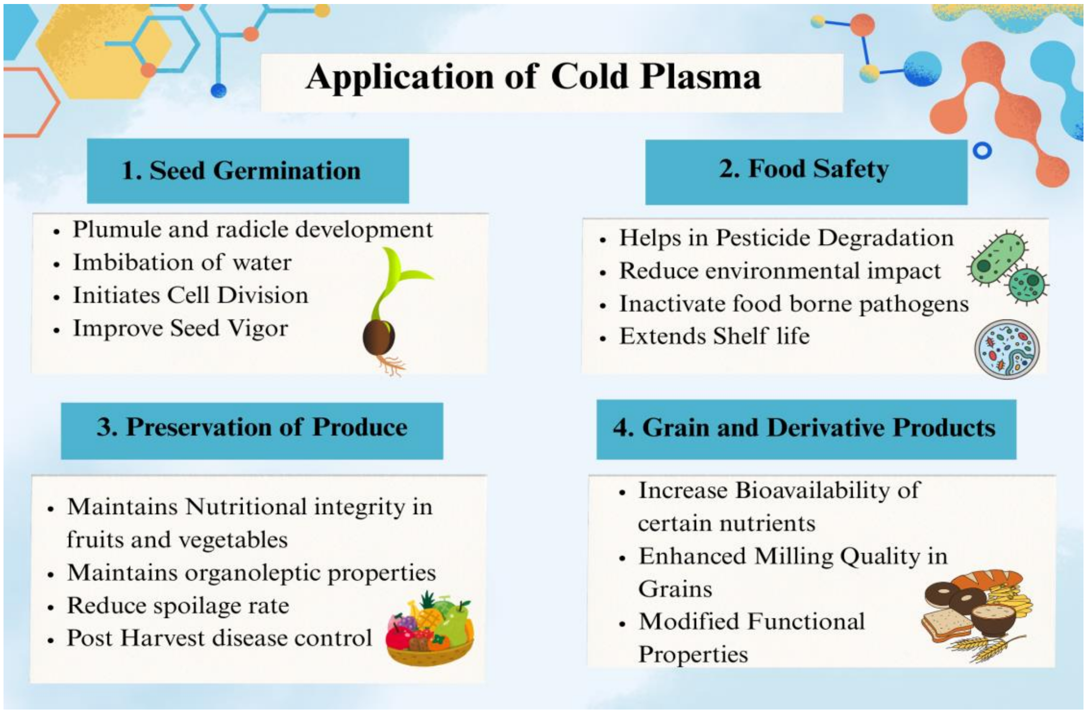


Figure 2: Applications of Cold Plasma in Food and Agriculture.

Seed Germination

Seed germination refers to the biological process through which the embryo present inside a grain develops into a plumule and a radicle. During this process, seeds absorb water, which causes the previously inactive skins to swell and initiates the division of cell. The young root emerges after the seed pore region and start to grow downward into the surrounding material, with continued development, it forms the root system, which responsible for supplying water and nutrient to the plant throughout its life cycle (Joshi., 2018).

Seed Dormancy and the Role of Plasma Treatment

Seed dormancy is a natural characteristic of grains that enables plant species to survive and reproduce under unfavourable environmental conditions. Plasma treatment produces several active agents capable of overcoming dormancy, including ultraviolet radiation, reactive radicals, and plasma-induced chemical reactions. Recent studies have investigated the effects of cold plasma (CP) at various species. As a result, CP treatment can effectively protect seeds against drought-induced stress. It has also proven beneficial in lowering overall germination rates. Several studies have reported that plasma-treatment seeds germinate more rapidly than untreated ones. Reactive plasma species are able to pass through the seed coat and exerting a strong influence on internal cellular structures. In addition, plasma treatment also leads to surface etching of the seed coat, which facilitate the entry of water and oxygen into the embryo, thereby stimulating sprouting. Plasma treatment is also found to disrupt cellular wall stability and alter enzyme activities, helping seeds to break dormancy and initiate germination (Singh et al., 2022). Cold plasma further supports germination and early seedling development. These positive effects are associated with a reduction in fungal contamination of seeds, changes in the physicochemical and biochemical properties of seed coats (such as increased hydrophilicity), and changes in Redox regulator mechanisms and plant hormones patterns (Kocira et al., 2022). Helium based cold plasma treatment has demonstrated strong potential in increasing wheat yield. It improve germination efficiency, promotes plant growth, and enhances physiological quality, ultimately leading to higher production of grain and improved resistance to pests and mycotoxins.

Peanuts seeds also respond positively to CP treatment. Significant improvements have been observed in germination percentage, seedling growth parameters, plant growth potential, dry biomass accumulation, and vegetable development. At later growth stages, CP treatment enhanced plant height, stem thickness, root biomass at harvest and total yield under field conditions. Short plasma exposure times (30-60 s) have been found to markedly improve seed sprouting characteristics and early-stage development of wheat seedlings.These effects depend on the plasma treatment method and the duration of post-treatment exposure in a closed reactor. The optimal method consisted of applying non-contact plasma application for 60 seconds, followed by a 24-hour period during which the plasma derived substance remained interaction with the seeds. This method increased wheat germination by 14.7 compared to untreated controls and also improved several growth-related parameters. Consequently, CP treatment may serve as a suitable alternative to conventional pre-sowing seed treatments in agriculture (Los et al., 2019). Under ideal conditions, plasma application alters the surface of wheat seeds by adding oxygen-containing reactive groups, mainly via the oxidation of the seed's natural lipids. This surface modification allows water to penetrate the seed pericarp more easily, leading to a reduced water contact angle and enhance water absorption. Overall, the plasma reaction process offers several advantages: it does not damage seeds, can be applied to a wide range of crop species, can be applied to a broad spectrum of crop species, and is ecologically friendly and sustainable.

Grains and derivative products

The effect of cold plasma treatment on black gram was examined by (Sarangapani et al., 2016). Their findings indicated that cold plasma significantly improved cooking efficiency by reducing both cooking time and grain hardness. Specifically, the cooking duration of black gram increased from 30.25 to 20.45 minutes, while hardness values declined from 22.50 to 12.36 N. This reduction in hardness was attributed to greater leaching of short-chain amylopectin compared to amylose. Moreover, the shortened cooking time was mainly due to starch depolymerization and damage to the surface structure of cereal grains caused by plasma exposure. According to another study, plasma treatment enhanced water absorption capacity after 4 hours of soaking, which was associated with the formation of simple carbohydrates. In the addition, plasma induced-surface depolymerization and etching increase amylase activity and improved the water uptake ability of brown rice up to 1.21-fold (Lee et al., 2016). Plasma treatment has also shown noticeable effects on intermediate Grin products such as flour. For instance, Basmati Rice flour, with longer exposure time and higher plasma energy levels the water-holding capacity increases. (Thirumdas et al., 2016). Similarly, cold plasma treatment of parboiled rice resulted in reduced amylase content, while improvements were observed in flour wetting behaviour and the release of phenolic compounds, ranging from 30.34 to 27.89% (Sarangapani et al., 2016). Various grains and legumes were analysed for contamination by *Aspergillus* and *Penicillium*. A significant logarithmic reduction in microbial load was recorded following 15 minutes of plasma treatment. Cold plasma is recognised as highly effective method for lowering mould growth and mycotoxin levels among different varieties of rice grains. In one investigation, rice grains intentionally inoculated with moulds were when applicable to cold plasma treatment, the growth of *Rhizopus oryzae, Fusarium graminearum Aspergillus niger, and penicillium verrucosum* was markedly suppressed. Additionally, electrical conductivity (EC) and malondialdehyde levels in rice grains increased by 30.14 % and 103.27 % respectively. However, the germination of seed was observed to decrease when treatment duration reached 8 minutes (Guo et al., 2023). The functional, proximate, antinutritional, thermal and rheological characteristics was also found to alter when cold plasma exposure of pearl millet flour occurs. The treatment significantly reduced antinutritional components such as phytic acid and tannins. Furthermore, samples treated with plasma exhibited shear-thinning behaviour, reflecting enhanced elastic properties. Improvements were also reported in functional characteristics, including capacity of water and oil absorption, emulsifying ability, and foaming capability (Sarkar et al., 2023).

Pesticide degradation

Certain foods naturally contain toxic compounds, such as goitrogens, inhibitors, saponins, trypsin and lectins. Additionally, harmful substance like mycotoxins, endocrine-disrupting chemicals, and pesticides are precent in various food and water system, posing significant risks to health and safety of consumer. Currently, very few non-thermal methods are available for removing food hazards, including which is cold plasma that is of considerable potential. The cold plasma technique is also as effective technique to remove or reduce pesticide residues on vegetables (Sarangapani et al., 2016). The degrading of pesticides by cold plasma is associated with the production of reactive oxygen and nitrogen species (ROS and RNS). Pesticides consist of diverse chemical compounds and are extensively applied in agriculture to safeguard crop and prolong shelf life. However, resistance to pesticides necessitates higher application rates. In the food industry, pesticide residues are a serious concern due to potential risks they pose to human health (Yang et al., 2012). Pesticides are primarily applied in agriculture crops to minimize losses in grains caused by certain insects, but many of the compounds also pose health implications to consumer health. Cold plasma has successfully cleaned various food items of pesticide residues (Sarangapani et al., 2016). Plasma treatment given at 80 KV for 5 minutes, results in removal of pesticide residues on blueberries effectively. Under these treatment conditions, appropriate change in nutritional quality attributes were observed. These findings indicate that cold plasma treatment at 60 KV for 5 minutes and 80 KV for 60 seconds can maintain the nutritional quality of blueberries (Sarangapani et al., 2016). Pesticide in water were effectively broken down using the technique of dielectric barrier discharge (DBD) plasma at atmospheric pressure in air. The discharge, working at high voltages, acted as a rapid and efficient source of reactive oxygen species, reactive nitrogen species, and other plasma generated particles. The degradation yielding simpler chemical compounds as products (Sarangapani et al., 2016). Research has shown that cold plasma treatment effectively lowers organophosphorus pesticide levels without producing any negative, harmful and or unwanted impacts on the visual quality or texture of agricultural produce (Azzaz et al., 2018).

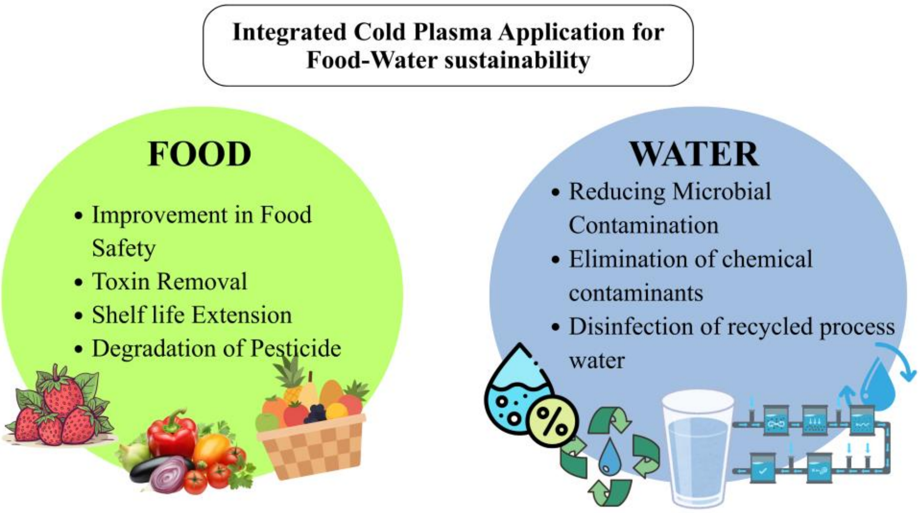


Figure 3: Integrated applications of cold plasma for food–water sustainability.

Fruit and vegetables

Worldwide, fruits and vegetables are extensively used up by human beings, and most fruits are eaten in their raw form, which raises concerns related to quality and food safety. Traditionally, fruits and vegetables are cleaned by washing and also by the use of certain chemical for surface disinfection. Cold plasma technology has emerged as an effective alternative to both chlorine-based treatments and water for the disinfection of fruits and vegetables. A variety of fruits and vegetables, such as berries, melons, pears, kiwis, and cherries have been treated using cold plasma. Research findings indicate that cold plasma treatment can influence the surface PH and acidity of the final product. Moreover, during storage, treated produce may exhibit certain changes in structural characteristics and colour (Nisha et al., 2019). Studies have shown that increasing the voltage and time of treatment during plasma treatment process can significantly reduce bacterial populations on fresh produce, with minimal to no effects on physical properties like colour and texture (Shanker et al., 2023). A gas plasma using dielectric barrier discharge was applied on the exterior surface of fresh-cut lemon. Treating each side of the lemon for 15 minutes increased its shelf life up to four days at the temperature of 10 °C, with minor alterations in different parameters of quality (Fernanda et al., 2022). The extended shelf life was attributed to the slower growth of pathogenic microbes including mesophilic and psychrophilic microbes. Additionally, this treatment effectively inactivated other fungal organisms, including Penicillium and Botrytis, in fruits and vegetables (Akaber et al., 2024). However, several studies have reported that cold plasma treatment does not cause any significant alterations in the antioxidant potential and overall compositional contents of treated fruits (Chutia et al., 2020).

Conclusion

Over the past two decades, the technology of cold plasma in food sterilization has gained substantial importance in the food industry, which seeks gentle yet efficient processing methods. Cold plasma treatment shown to have positive influence on seed germination, early growth, and overall plant development in crops like wheat, soyabean, and peanuts. It enhances water absorption, nutrient utilization, and biochemical activity, while reducing cooking time and grain hardness in cereals and legumes. Additionally, it lowers microbial contamination and decreases antinutritional compounds, making it a sustainable and eco-friendly alternative to traditional seed treatments and grain processing methods. In fruits and vegetables, cold plasma effectively reduces microbial load and pesticide residues, extending shelf life without compromising colour, texture or nutritional content. Being a non-thermal and chemical free approach, it preserves freshness and sensory qualities better than conventional heat or chemical treatments. While scaling up for industrial applications remain a challenge, cold plasma shows strong promise for safe, high quality and environmentally friendly food processing.

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