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A comprehensive review on cold plasma applications in the food industry

Raju Sasikumar, *[a] Selva Kumar T.,[ab] Irengbam Barun Mangang,[c] G. Kaviarasu,[a] Ravinder Kaushik,[d] Paul Mansingh,[e] Vidisha Tomer[f] and Amit K. Jaiswal *[gh]

Cold plasma (CP) technology has gained attention as a non-thermal, sustainable approach for microbial decontamination and functional enhancement in food systems. Conventional thermal processing methods often compromise food quality through nutrient degradation, textural changes, and the formation of harmful by-products. In contrast, cold plasma operates at near-room temperatures and utilizes ionized gases to generate reactive oxygen and nitrogen species (ROS and RNS), which effectively inactivate microorganisms and enzymes without significant heat input. This review aims to provide a comprehensive evaluation of cold plasma applications across various food categories, including fresh produce, dairy, meat, cereals, juices, and packaging systems.

[a]*Department of Agribusiness Management and Food Technology, North-Eastern Hill University (NEHU), Tura Campus, Chasingre 794002, Tura, WGH, Meghalaya, India. E-mail: sashibiofoodster@gmail.com*

[b]*Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai 600062, India*

[c]*Kelappaji College of Agricultural Engineering and Food Technology, Kerala Agricultural University, Malappuram, India*

[d]*Department of Allied Health Sciences, School of Health Sciences and Technology, UPES, Dehradun, Uttarakhand 248007, India*

[e]*Department of Agricultural Extension & Economics, VIT School of Agricultural Innovations and Advanced Learning (VAIAL), Vellore Institute of Technology, Vellore 632014, India*

[f]*Department of Horticulture and Food Science, VIT School of Agricultural Innovations and Advanced Learning, Vellore Institute of Technology, Vellore 632014, Tamil Nadu, India*

[g]*School of Food Science and Environmental Health, Faculty of Sciences and Health, Technological University Dublin, City Campus, Central Quad, Grangegorman, Dublin, D07 ADY7, Ireland. E-mail: amit.jaiswal@tudublin.ie*

[h]*Centre for Sustainable Packaging and Bioproducts (CSPB), Technological University Dublin, City Campus, Dublin, Ireland*

Raju Sasikumar

Dr R. Sasikumar is a professional Food Technologist who having wide experiences and expertise in the area of Food Processing Technology with 21 years of experience in both industry and academic sectors. As a result, he developed number of food products, contributed key area such as quality assurance and safety, technology transfer and commercialization to improve livelihood of tribes in Meghalaya, India. He published 40 research articles in reputed peer review journals, authored 7 textbooks, 12 R&D projects; fifty papers were presented in international conferences. For his achievements, he filed three patents and commercialized into different food processing companies.

Selva Kumar T.

Mr Selva Kumar T is a researcher specializing in nanobiotechnology, and food processing technologies. His work focuses on antimicrobial, antioxidant studies using nanotechnology, microbial inactivation methods, including ultrasound-assisted microwave treatments, fermentation processes, and phytosurfactants. With a strong analytical approach, he optimize food-processing techniques to enhance phytonutrients. He actively contributes to interdisciplinary research aligning food sustainability with technological advancements by integrating nanotechnology. His expertise extends to edible coatings and bioplastics in packaging applications. Passionate about scientific communication, he published all his findings in reputed journals and an active reviewer for various journals.

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Mechanistically, CP disrupts microbial membranes through oxidative stress, damaging lipids, proteins, and DNA. Treatment durations as short as 60 seconds have achieved >5-log reductions in *E. coli*, *Listeria monocytogenes*, and *Salmonella* in products such as apple juice, lettuce, and dairy. Enzymes such as peroxidase and polyphenol oxidase show activity reductions of up to 70% under atmospheric dielectric barrier discharge (DBD) plasma at 6.9 kV for less than 1 minute. CP also induces beneficial structural changes in proteins and starches. For instance, cross-linking of starch granules improves gelatinization and water absorption, shortening rice cooking time by 27.5%. In protein systems, CP treatment enhances solubility by up to 12.7%, and emulsification and foaming capacity are also improved, particularly in soy and pea protein isolates. In-package cold plasma technology enables microbial decontamination within sealed environments, maintaining product integrity and extending shelf life up to 14 days in treated chicken and fresh-cut melon. While CP offers a low-energy, chemical-free solution aligned with clean-label and sustainability goals, challenges remain in process standardization, by-product control, and scale-up. Nonetheless, its compatibility with sustainable development targets, including SDG 2 (Zero Hunger), SDG 3 (Good Health), SDG 7 (Clean Energy), and SDG 12 (Responsible Consumption), reinforces its potential as

Irengbam Barun Mangang

Dr I. Barun Mangang is a young and dynamic Food Technologist. He has published more than 14 research papers, 4 book chapters, with over 3 years of post-doctoral experience in research and academics. Presently, he is serving as Assistant Professor at Kelappaji College of Agricultural Engineering & Food Technology, Kerala Agricultural University, India. He has an active h-index of 6 and an i10-index of 3 with more than 85 citations since 2020. His expertise spans over freeze-drying, radio-frequency heating, ultrasound-assisted thin bed drying, emulsification, and storage. He is an active reviewer for multiple reputed national and international journals.

Vidisha Tomer

Dr Vidisha Tomer is currently working as an Assistant Professor in the Department of Horticulture and Food Science, VIT Vellore, India. She has 8+ years of experience in teaching and research. She works on the development of functional foods. She completed her PhD in Food and Nutrition from Punjab Agricultural University, Ludhiana. She was awarded an INSPIRE Fellowship by the DST, India. She has authored various publications, book chapters and books with publishers of repute. She is currently an active member of scientific societies including the Nutrition Society of India, the Indian Dietetic Association, and the American Society of Nutrition.

Paul Mansingh

Dr Paul Mansingh J is a distinguished academic and researcher currently serving as a Professor in the Department of Agricultural Extension and Economics at VIT, India. With a career spanning a decade in agricultural extension and rural development, he has made significant contributions to research, policy, and academics. He has published 50+ research articles in renowned journals, making substantial contributions to Economic, Environmental Sustainability, Agripreneurship, Geographical Indication. Also involved in 6 industrial consultancy projects, working closely with stakeholders for agricultural development. Before 2019, he contributed significantly to the Ethiopian Government University, where he engaged in research and academic mentorship.

Amit K. Jaiswal

Dr Amit K. Jaiswal is a Lecturer at the School of Food Science and Environmental Health, TU Dublin–City Campus. Recognised among the world's top 1% most cited researchers by Clarivate (2023–2024) and Stanford's top 2% scientists (2021–2024), his research focuses on biorefinery-based conversion of lignocellulosic biomass into bio-based chemicals, biofuels, and biomaterials. He develops sustainable innovations in packaging, coatings, energy storage, adhesives, and water purification. His work integrates Safe and Sustainable by Design principles, life cycle assessment, and techno-economic analysis. He has published over 150 peer-reviewed articles, 50 book chapters, and 5 books, with 12,000+ citations and an h-index above 50.

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a next-generation food processing technology. Future studies need to focus on combining CP with other innovative technologies, addressing long-term safety concerns, and enhancing CP configurations for various food matrices. To ensure the public acceptance of CP as an innovative food processing technology, interdisciplinary partnerships and regulatory frameworks must be established.

Sustainability spotlight

The growing demand for minimally processed, safe, and high-quality food highlights the need for sustainable alternatives to traditional thermal processing. This comprehensive review of cold plasma, a non-thermal technology that ensures microbial safety, retains nutritional value, and reduces energy consumption in food processing. Unlike conventional methods, cold plasma minimizes environmental impact and supports the development of eco-friendly packaging and waste reduction systems. The integration of this technology aligns with the UN Sustainable Development Goals: SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production), emphasizing its relevance in advancing sustainable food systems. Cold plasma's adaptability across diverse food sectors makes it a versatile and future-ready solution for climate-resilient food processing.

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1 Introduction

Conventional food processing methods involve exposing food to high temperatures.[1] Blanching, pasteurization, heat sterilization, extrusion cooking, evaporation, and distillation are heat-processing techniques that involve the use of steam or water. Dehydration, baking, and roasting are forms of processing that involve the use of hot air. Food processing also involves frying, in which oils are used. These methods are widely used in the food-processing sector to increase shelf life by inhibiting microbial or biochemical changes. Processing of raw materials reduces waste generation. Food processing industries improve the well-being of humankind by generating income for individuals. Despite these advantages, conventional methods have various disadvantages that go hand in hand *viz.* protein degradation, loss of vitamins, and oxidation of lipids.[1,2] Some of the thermal techniques *viz.* baking, roasting, and frying were also proven to produce chemical toxicants in starchy and proteinaceous foods.[3–5] Hence, there is a need for the use of non-thermal techniques to aid thermal techniques or act alone. Some non-thermal techniques include the use of UV-C for surface disinfection, ultrasound pretreatment, irradiation, cold plasma, pulsed electric field, and high-pressure processing.[6]

Food processing industries have been investigating the development of novel non-thermal processing technologies for a considerable amount of time to meet the ever-increasing demands of consumers.[7,8] This ensures the quality and safety of processed food products sold on the market. The main aim behind developing novel technologies is to retain the amount of nutrients present in the food before processing it until it reaches the consumer. They also inhibit or destroy microorganisms present, and offer an environmentally friendly option.[9–12] This is a disadvantage when it comes to thermal processing methods, considering the loss in food quality. A distinguished development in the evolution of non-thermal processing technologies is the application of cold plasma for food decontamination and for the enhancement of food properties.

Cold plasma technology is developing as an innovative tool in the food industry, offering a novel, non-thermal method for food preservation and safety. This technology generates reactive species at ambient temperatures, which effectively inactivate a wide range of pathogens, including bacteria, viruses, and fungi, without compromising the nutritional and sensory qualities of food products. Unlike traditional thermal treatments, cold plasma preserves the texture, flavour, and nutritional content of foods, making it particularly valuable for fresh produce, meats, and ready-to-eat meals. Additionally, its application extends to packaging materials, enhancing their antimicrobial properties and extending the shelf life of perishable goods. As research advances, cold plasma technology is poised to become a pivotal element in modern food processing, ensuring safer and longer-lasting food products while maintaining high quality standards.[13]

Solid has the lowest energy, and as it gets more energy, it can be converted to liquid and then to gas. Plasma is the fourth state of matter that comes after solids, liquids, and gases.[14] Gas requires an extremely high amount of energy to convert into plasma. The ionized gas contains atoms, electrons, free radicals, gas molecules, photons, and positive and negative ions, in balanced concentration, making plasma electrically neutral.[15,16] Charged particles are highly electrified in nature, allowing plasma to conduct electricity. When the gases are fully ionized, extremely high-temperature plasma is created, generating temperatures of millions of °C. Partial ionization leads to the formation of thermal and non-thermal plasma. If the electrons and the heavy particles (gas and ions) remain at the same temperature, they are termed thermal plasma. However, in cold plasma also called non-thermal plasma, the electrons lie at a higher temperature than the heavy particles, which are at room temperature.[16]

The majority of the reviews that are now available are either product-specific or restricted to microbial inactivation, despite the fact that the amount of research on cold plasma applications in food systems is expanding. In contrast, this review provides a thorough assessment across a variety of food matrices, including wastewater treatment, dairy, meat, fruits, vegetables, and grain germination. Also, this review is distinctively positioned to function as a useful resource for scientists, food processing engineers, researchers and food technologists due to the incorporation of in-package plasma treatments, sustainability implications in line with the UN SDGs,

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a thorough discussion of industrial regulatory challenges, and the scaling-up.

2 Principle of cold plasma

Cold plasma is non-thermal and operates near atmospheric pressure, making it unique from other plasma technologies adopted.[17] The reason behind this is the existence of two processes during its creation *viz.* ionization and recombination. During ionization, there is a partial breakdown of gas molecules, followed by recombination, where the ionization energy is converted to heat, chemical energy, and then light.[18]

The ionization mechanism occurs primarily due to electron impact, wherein the kinetic energy of the impacting electron is more than the ionization potential. Ionization also occurs if two heavy particles collide or during photoionization when a neutral atom collides with a high-energy photon. This is where recombination occurs: when high-energy electrons come back to positive ions, resulting in the formation of neutral molecules, which have all the ionization energy that was present. The energy needs to be dissipated, and hence, there is this formation of neutral molecules and excited molecules, thereby producing cold plasma.

Disrupting the cytoplasmic membrane of bacteria is the primary goal of physical and chemical treatments.[19,20] Any living organism's substantial barrier to its surroundings is its cytoplasmic membrane. It protects them by preventing the entry of foreign organisms from the surrounding environment. These membranes experience oxidative reactions caused by reactive oxygen species produced by plasma.[21]

Reactive oxygen species (ROS) are generated by cold plasma through the processes of ionization and recombination. During ionization, gas molecules are partially broken down into ions and free electrons. This breakdown process leads to the formation of reactive species, including various forms of oxygen such as atomic oxygen (O), singlet oxygen ($O_2{}^1\Delta g$), ozone (O_3), and hydroxyl radicals ($OH^\bullet$). Following ionization, recombination occurs, wherein the energy released from the ionization process is converted into heat, chemical energy, and light. This energy conversion sustains the presence of reactive oxygen species, which play a crucial role in the antimicrobial and oxidative mechanisms of cold plasma, making it highly effective for applications in the food industry.[22]

Cold plasma technology affects microbial cell structures and biochemical pathways through ionization, free radical formation, and cell membrane penetration. The process begins with the ionization of gas molecules (*e.g.*, oxygen, nitrogen, and argon) under an electric field, generating a variety of reactive species. Key reactions include electron impact ionization ($e^- + O_2 \rightarrow O_2^+ + 2e^-$), dissociation of oxygen ($e^- + O_2 \rightarrow 2O + e^-$), and the formation of ozone ($O + O_2 \rightarrow O_3$).[23] These reactions produce reactive oxygen species (ROS) such as atomic oxygen (O), hydroxyl radicals (OH), and ozone (O_3), as well as reactive nitrogen species (RNS), such as nitric oxide (NO) and nitrogen dioxide (NO_2). These reactive species penetrate microbial cell membranes, causing oxidative damage to lipids through lipid peroxidation, which disrupts membrane integrity and increases permeability. Proteins within the cell membrane are oxidized, impairing their function and further destabilizing the cell. Additionally, ROS and RNS induce DNA damage, including strand breaks and base modifications, which lead to mutations and hinder replication and transcription processes. The combined oxidative stress on lipids, proteins, and DNA culminates in cellular dysfunction and death, effectively inactivating the microorganisms.[24]

They break ionic and chemical connections with the phospholipids and proteins found in cell membranes, which causes the membranes of the microorganisms to be destroyed and generates structural changes in the proteins present. The formation of pores inside membranes leads to osmotic imbalance, and the entry of reactive oxygen species into cells further damages various organelles, such as the mitochondria and the nucleus.[25] Once the plasma punctures the cells' outer membrane, their internal matter seeps out through the membrane, increasing the vulnerability of the cells to the surrounding reactive environment. Cold plasma treatment has been carried out against bacterial spores and has the ability to increase membrane permeability, as reported in the case of *Salmonella* and *Listeria monocytogenes*.[26] This technology effectively eliminates a significant population of spoilage organisms present in food. These non-thermal plasmas work well as sterilizing and decontaminating agents. They have the ability to quickly and effectively neutralize a lot of bacteria. The type of microorganisms present, the plasma power density, and the kind of supporting medium all affect how long the decontamination process should last.[27]

3 Types of cold plasma

3.1 Microplasma

Microplasma is a scaled-down form of plasma with dimensions that can be in the tens,[28] hundreds, or even thousands of micrometers.[29] Creation of ROS at the atmospheric level and ambient temperature is made possible by this technology, which also uses relatively little electricity. Microplasmas are best for surface cleaning and can be operated with one or more plasmas integrated into them.[30,31] Non-thermal microplasmas can be easily sustained and controlled under normal circumstances and can keep their state at typical pressures and temperatures. Consequently, they can be applied in commercial, industrial, and medical settings.[32,33]

3.2 Gliding arc discharge plasma

Compared to other non-equilibrium discharges, the density, power, and operational pressure of this plasma are relatively higher.[34] It is produced by injecting the gas between two electrodes. High electron temperature, low gas temperature, and the potential to stimulate specific chemical reactions without quenching are further features of this technology. This technique can continuously generate short-lived reactive species, and as a result, it can be used to treat surfaces and liquids to eradicate probable bacterial contamination.[35]

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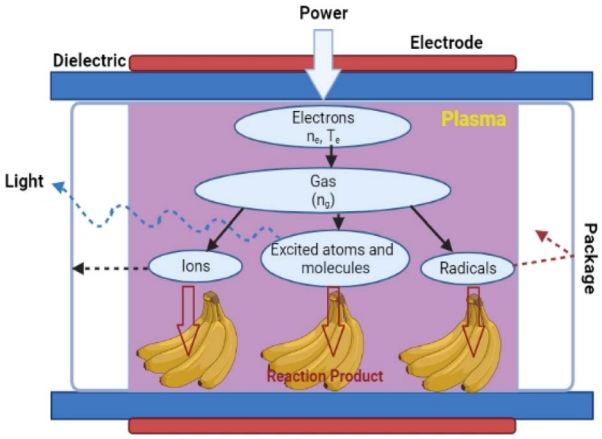

Fig. 1 In-package cold plasma treatment.[40]

3.3 Dielectric barrier discharge plasma

Through ionization, dielectric barrier discharge can be created in a variety of media at high frequency and high electric discharge, producing non-equilibrium plasma at the atmospheric level.[36,37] The main distinction in this technology is the barrier that separates the electrodes from the discharge (Fig. 1). Dielectric barrier discharge plasmas play a significant part in inactivating the bacterial spores, ensuring the safety of the finished processed food products.[38,39]

3.4 Corona discharge plasma

Corona discharge plasma, which is capable of being generated at high voltage, is only used in non-homogeneous media. It generates when a strong electric field around a sharp electrode ionizes the electrons in nearby gas molecules or atoms.[41] It is characterized by the formation of photons, electric fields, charged species, glow discharge, streamer discharge, radicals, and other species. Due to the high reactivity and concentrated intensity of the discharge region, food processing is usually performed downstream of the high-voltage gap, rather than directly between the electrodes. In certain systems, a ground screen is placed between the processed food sample and the electrodes. Only neutral species can flow through the ground screen electrode because the ground screen blocks the passage of all charged species and the majority of electric flux densities.[42] This technique of plasma generation is simple to implement and cost-effective, so it's applicable in various industries for surface decontamination, microbial decontamination, electro-precipitation, *etc.*, but it is limited to nonhomogeneous tiny areas. However, its application is typically limited to non-uniform or limited treatment zones, which limits scalability for bulk processing.[43]

3.5 Radio-Frequency (RF) plasma

Radio-Frequency (RF) plasma generates the high-frequency discharge. The RF plasma system uses an intense electrical pulse across a wide range of voltages and electrical settings to ionize gas. A coil-shaped antenna produces radio-frequency waves in capacitively linked plasma. This coil generates relatively low-temperature, high-frequency plasma with dense atomic particles. The electrodes generate the plasma when supplied with an extreme frequency of 13.56 MHz and an average RF power of 50–100 W.[44] Foods are exposed to RF plasma directly during plasma generation because the electrodes cannot spatially restrict it. In electrodeless operation with an external or insulated electrode, the primary benefit is that RF prevents reactive reactions caused by metal electrodes. Compared to corona and gliding arc discharge, RF plasma discharge devices have a longer lifespan and the ability to carry out a variety of pressure and ion energy activities.[44]

3.6 Glow discharge

Glow discharge plasma is a non-thermal equilibrium discharge that usually operates at low pressure. In this type of plasma, the light emission pattern of the glow is separated into several layers between the cathode and anode electrodes. The pattern of illumination varies with gas pressure and gap distance. Design factors are crucial at atmospheric or high pressures since the glow is unstable at higher pressures and might turn into a spark.[45] The electron temperature of these low-current, high-voltage plasmas is still greater, even while the gas temperature reaches several thousand Kelvin.[46] This kind of plasma is utilized in glow discharge lasers, gas chromatography, ozone synthesis, plasma polymerization, material treatment, and as a molecular optical emission detector for gas chromatography.[47] It can be used to reduce harmful bacterial contamination of foods and surfaces that come into contact with them. It involves exposing the bacteria to a homogeneous glow discharge plasma in one environment, which has the ability to eliminate the bacteria and lower their population.[48]

3.7 Microwave discharge plasma

Electromagnetic radiation with a frequency between 300 MHz and 300 GHz commonly causes microwave discharges. A large-diameter plasma discharge at a low gas pressure is produced using this method. The shielding process is essential in this type of plasma discharge, but it can produce the plasma in place of electrodes. The components of the CP system included a parameter controller, cooling system, treatment chamber, vacuum pump, and components for generating microwaves. A gas mass flow rate controller regulates the pumping of the plasma-forming gases, nitrogen (N_2) or the helium (He) and oxygen (O_2) mixture ($He:O_2$), at a rate of 0.8 m^3 min^{-1}. The pressure inside the chamber is controlled by a vacuum valve and ranges from 500 to 30 000 Pa.[49] Compared to traditional heating, microwave energy has been utilized to pasteurize or sterilize food at lower temperatures and in less time. Either the discharge or its afterglow can undergo further plasma sterilization.[50]

4 Interactions of cold plasma with food components

4.1 Action of plasma on proteins

In addition to bacteria, the plasma can also be used on simpler biological substances such as enzymes. Enzymatic browning,

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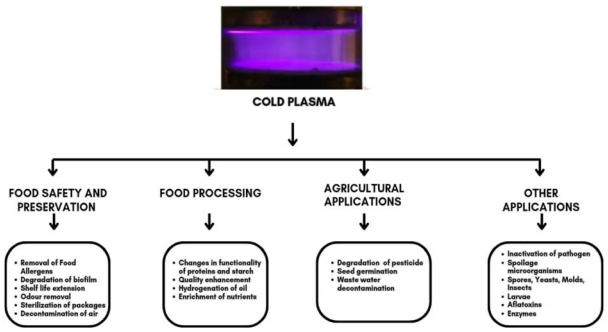

Fig. 2 Applications of cold plasma techniques.

which is regarded as a secondary loss during post-harvest handling and storage, is the primary cause of fruit and vegetable spoilage. The primary causes of enzymatic browning are endogenous enzymes, mainly polyphenol oxidase and peroxidase because they oxidize phenols.[51] Due to the breakdown potential of peptide bonds, it was discovered that the plasma had the ability to alter the 3D structure of proteins in trypsin enzymes.[52] After receiving a dose of cold plasma, a decrease in trypsin's enzymatic activity and increase in amino acid was noted. Enzymes are biocatalysts that can work with all the major classes of biomolecules that are present in food. Enzymatic activity should be taken into account while extending the shelf life of products. Cold plasma has been used in a number of prior attempts to extend food shelf life.[53]

Most food enzymes are proteins, which are polymers of amino acids arranged into intricate three-dimensional structures that are linked to their functioning. Any therapy that alters the molecular structure of an enzyme could have an impact on its ability to be inactivated. By using X-ray photoelectron spectroscopy (XPS), it has been demonstrated that L-alanine's direct exposure to argon plasma causes the COOH group and CNH_2 group to degrade.[54] The changes in the structural properties of protein are brought about by the reaction with ROS generated. According to an experiment by Jang *et al.*,[55] optical emission spectroscopy identified that excited atomic oxygen and nitride oxide were the primary components of a helium/oxygen mixture plasma, causing proteins to lose their activity. The ability of oxygen atoms in oxygen-containing plasma to pull hydrogen leads to the creation of radical sites in the protein-polymer chain. This makes the chain break subsequently, resulting in the formation of volatile compounds. It has also been suggested that proteins' C–H, C–N, and N–H bonds break down into CO_2, NO_2, and H_2O as a result of oxidation, resulting in the loss of structure as observed by infrared spectroscopy when casein and albumin proteins after exposure to RF oxygen plasma were analyzed.[56] It should also be noted that nitric oxides were also generated in the gaseous phase while operating in a nitrogen and oxygen filled plasma chamber. Experiments and computational models have been used to study the reaction mechanism of nitric oxide including its antibacterial and physiological effects. It has also been previously documented that exposure to nitric oxide in apples causes polyphenol oxidase to be inhibited.[57] Nitric oxide in the μM range or above has the potential to impair the activities of the enzyme by providing irreversible damage to the iron–sulfur bond present in bacterial metabolism.[58] It also inhibits the respiration of bacterial cells by binding the heme group to cytochrome oxidase. Thus, it can be confirmed that nitric oxide plays an important role in inactivating the enzymes besides ROS. However, the problem of nitric oxide oxidation to form nitrogen dioxide in a nitrogen and oxygen filled plasma chamber is a research gap that needs to be solved. Another research gap is process optimization of cold plasma in various foods, since different foods contain a range of ions that may act against the action of cold plasma.

4.2 Action of plasma on carbohydrates

The quality of various food products is defined and maintained in large part by carbohydrates. All of the reducing sugars, including fructose and glucose, as well as the non-reducing sucrose, were degraded because of the cold plasma treatment of cashew apple juice.[59] According to the study, the primary pathway for degradation that leads to the breaking of glycoside linkages, depolymerization of the macromolecule, and oxidation of functional groups to produce hydroperoxides, lactones, and carbonyl and carboxyl chemicals is ozonolysis. An increase in the rate of water uptake in black gram increases the water binding sites due to the plasma reactive species by fragmenting the starch and protein molecules.[60] A shorter boiling time for brown rice, due to large incorporation of polar groups between the molecules of starch leading to faster gelatinization, was also reported.[61,62]

The functional characteristics of starches are changed to improve their effectiveness as food additives in a variety of meal preparations. The usage of modified starches was found to enhance the tensile strength and mechanical qualities of starch films.[63] Natural polymers that are readily available for the preparation of modified starches are hypersensitive to chemicals, especially to strong acids used for surface etching. Therefore, transformation was carried out from smooth hydrophobic surfaces into rough hydrophilic ones using weak chemicals. Cold plasma technology can be used instead of dry etching to clean and modify the surface of biopolymers.[64] Two primary processes—depolymerisation and cross-linking of starch granules—modify starch. The breakdown of glycoside bonds near side chains on amylopectin might cause the depolymerisation of starch granules. The solid starch granules' crystallinity is significantly impacted by the plasma treatment. The molecular weight of the plasma-treated starch granules decreases more dramatically.

Cross-linking agents facilitate the union of starch molecules primarily by disrupting weaker hydrogen bonds and promoting the formation of stronger covalent linkages.[65] Recent studies have shown that starch can be effectively modified by cold plasma treatment under varying pressure and exposure times, resulting in altered structural and functional characteristics.[66] The cross-linking mechanism involves reactive oxygen and nitrogen species (RONS) generated during plasma exposure, which oxidize hydroxyl groups and lead to

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Table 1 Applications of cold plasma

Specific name	Type of cold plasma	Matrix	Feed gas	Quantitative details	References
Enzyme					
Papain enzyme	Dichlorosilane-RF cold plasma	Polyethylene and glass surfaces	Dichlorosilane/ argon	Enzyme immobilization activity maintained after several wash Quantity: N/A	71
Peroxidase enzyme	Atmospheric cold plasma (DBD)	Tomato peroxidase	Ambient air (46% RH, 25 °C)	t_{50} value of 0.89 min accounted for the rapid enzyme inactivation at 50 kV	72
Alkaline phosphatase	Atmospheric cold plasma (DBD)	Commercial lyophilized powder from bovine intestinal mucosa	Ambient air	Enzyme inactivation in 300 s at 60 kV	73
Peroxidase and pectinmethylesterase	Atmospheric cold plasma (DBD)	Fresh-cut melon	Ambient air (22 °C and 60% of RH)	Peroxidase and pectinmethylesterase inhibited by 17, 7%, respectively, at 15 kV peak to peak and a dominant frequency of 12.5 kHz	74
Lysozyme	Atmospheric cold plasma (DBD) and plasma jet (APPJ)	Commercial lyophilized powder	N_2 (99.99%) and ambient air	With N_2-APPJ for 12 min, α-helix increased to 70.4% from the original 51.3% With N_2-DBD for 12 min, α-helix dropped to 27.1%	75
Hydrolytic enzymes (amylase, protease, and phytase)	Atmospheric cold plasma (DBD)	Mung bean germination	Ambient air (24 ± 1 °C)	25.2% increase in amylase activity for 60 W 20 min Increase in protease enzyme activity by 36.7% in 60 W 20 min	76
Red yeast invertase	High voltage atmospheric cold plasma	Grape juice	Modified air (MA65, 65% O_2, 30% CO_2, 5% O_2)	>96% inactive after 75 s at 60 kV	77
Peroxidase	Atmospheric cold plasma jet (APPJ)	Commercial lyophilized powder of horseradish peroxidase	98% Ar and 2% O_2	Enzyme activity decreased by 17% @ 7 kV for 10 min	78
Microbial inactivation					
D. radiodurans	Low-power oxygen plasma	Commercial *Deinococcus radiodurans* strain R1	Martian air analogue (95.48% CO_2, 2.51% N_2, and 2.01% ar) and O_2 (99.99%)	Reduction by 99.999% at 25 W, ∼45 mTorr, 90 min 6-log reduction of $\sim 10^6$ viable cells	79
Chromobacterium violaceum	Gas discharge plasma	*Chromobacterium violaceum* biofilm (4 days old)	Industrial grade He and N_2	Rapid initial decline in the CFU per milliliter (*D* value of 2.3 min) that is followed by a subsequent decline (second phase) of a *D*-value (D2) of 37.4 min	80
Bacteriophage lambda (λ phage)	Atmospheric cold plasma (DBD)	λ phage induced from λ-lysogen cells, *E. coli* M65	Ambient air	6 log reduction in 20 s and *D* value of 3 s at 40 kV_{p-p}, 2 kHz, and 8.7 W	81
Bacillus cereus and *Bacillus anthracis* spores	Micro second pulsed atmospheric cold plasma (DBD)	*Bacillus cereus* (ATCC 6464) and *Bacillus anthracis* (Sterne strain 7702) spores	Ambient air	5 log reduction in less than a minute of treatment at 30 kV_{p-p}, 1.3 kHz, 1.2 μs, and 0.3 W cm^{-2}	82
E. coli	Atmospheric cold plasma microjet	*E.coli* sample	Compressed air at 5 standard liters per minute (slm)	*D*-value of 14 minutes at 20 kHz	83
Salmonella	Atmospheric cold plasma microjet	Salmonella suspension (10^5 CFUs) in carrots, cucumbers, and pears	Compressed air at a flow rate of 5 slm	*D*-value of <4 s at 30 mA at 500 V	84

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Table 1 (*Contd.*)

Specific name	Type of cold plasma	Matrix	Feed gas	Quantitative details	References
E. coli	In-package atmospheric cold plasma (DBD)	*Escherichia coli* ATCC 25922	Ambient air	20 s of direct and 45 s of indirect at 40 kV results in 7 log CFU ml^{-1} reduction	85
E. coli inoculated at 10^5 and 10^7 cfu g^{-1}	Atmospheric pressure cold plasma	Fresh lettuce, carrot, tomato	Argon	1.6 log CFU ml^{-1} reduction of *E. coli* at 12.83 kV for 10 min, 60 Hz Inoculation level had an effect on the degree of inactivation	86
DNA of *E. coli* and *L. monocytogenes*	High voltage atmospheric cold plasma (DBD)	10^8 CFU mL^{-1}, *E. coli* ATCC 25922, *E. coli* NCTC 12900 and *L. monocytogenes* NCTC11994	Ambient air (gas mix 1), 90% N_2 + 10% O_2 (gas mix 2) and 65% O_2 + 30% CO_2 + 5% N_2 (gas mix 3)	For *E. coli* ATCC 25922: gas mixture 3 is most effective with 6.6 log CFU ml^{-1} reduction at 70 kV For L.*monocytogenes*: gas mix 1 & 3 (reduction below detection level) at 70 kV For L.*monocytogenes*: all gas mixtures achieved inactivation below detection level at 70 kV	87
Salmonella enterica, *Listeria monocytogenes* and *Escherichia coli*	In-package atmospheric cold plasma (DBD)	Lettuce	Ambient air	ACP treatment for 30 s reduced bacterial populations in lettuce broth by 7 log CFU ml^{-1} at 40 kV ACP treatment for 300 s effectively reduced biofilm populations on lettuce by 5 log CFU ml^{-1} at 40 kV	88
E.coli and *Salmonella* inoculated at 10^5 log CFU g^{-1}	Micro jet atmospheric cold plasma	Lettuce	N_2, N_2–O_2 mixture (ratio = 4 : 1), He, and He–O_2 mixture (ratio = 98 : 2)	2.9 log CFU g^{-1} reduction of *E. coli* using N_2 at 900 W for 10 min 2.2 log CFU g^{-1} reduction of *Salmonella* using N_2 at 900 W for 10 min	89
Gram positive (*Staphylococcus epidermidis*, *Kocuria carniphila*, *Bacillus subtilis*)	Atmospheric cold plasma (DBD)	Biofilm of these bacteria	Argon at 3.1 slm	3.5 log CFU ml^{-1} reduction in 10 min for Gram negative bacteria at 1.82 MHz	90
Gram-negative (*Pseudomonas aeruginosa*, *Enterobacter cloacae*, *Pseudomonas libanensis*)				0.5–2 log CFU ml^{-1} reduction in 10 min for Gram positive bacteria at 1.82 MHz	
Ethanol red yeast	High voltage atmospheric cold plasma	Grape juice	Dry air or modified air (MA65, 65% O_2, 30% CO_2, 5% O_2)	Using MA65, >2 log CFU ml^{-1} reduction and using dry air, 0.5–2.0 log CFU ml^{-1} reduction was achieved at 18–80 kV	77
E. coli	Atmospheric cold plasma	Apple cider	Simulated air (SA) (80% N_2 + 20% O_2) and a combined gas (CG) of 90% N_2 + 10% O_2	5 log CFU ml^{-1} reduction in 120 s at 20 kV with an arc drop voltage of 2 kV with frequency ranging from 15 to 25 Hz Gas type has no significant difference in inactivation	91
Alicyclobacillus acidoterrestris	High voltage cold plasma discharge	Apple juice	Ambient air	4.14 log CFU ml^{-1} reduction in 7 s at 6.86 kV and complete inactivation in 240 s	92
Citrobacter freundii	RF cold plasma microjet	Apple juice	Argon 5.0 (purity ≥99.999%) as well as mixtures of argon and 0.025–0.1% oxygen at 5 slm	*Citrobacter freundii* reduction by 5 log CFU ml^{-1} at 65 V with capacitive coupling at 1.1 MHz	93
S. cerevisiae	High voltage atmospheric cold plasma	White Grape juice	Ambient air (46% RH, 24 °C)	7.4 log_{10} CFU mL^{-1} inactivation of *S. cerevisiae*	94

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Table 1 (*Contd.*)

Specific name	Type of cold plasma	Matrix	Feed gas	Quantitative details	References
Salmonella	In-package atmospheric cold plasma (DBD)	Grape tomato	Ambient air with changes in headspace air composition of MAP	3.8 and 1.5 log CFU ml^{-1} reduction using direct and indirect treatment, respectively, in grape tomato	95
Salmonella	In-package atmospheric cold plasma (DBD) in combination with zinc oxide	Steamed fish cake	Ambient air	2.4 log CFU g^{-1} reduction of *Salmonella* when treated with CP immediately after UV activated zinc oxide treatment, and more when fish cakes were cut into smaller pieces	96
Bioactives					
Antioxidant	Atmospheric cold plasma (DBD)	Kiwi fruit	Ambient air	Retention (no significant difference) of the antioxidant at 15 kV for 40 min	97
Anthocyanin	Micro jet atmospheric cold plasma	Blueberry juice	Dried, filtered air	Native mold count reduced by 0.8 to 1.6 log CFU g^{-1} and 1.5 to 2.0 log CFU g^{-1} compared to the control after 1 and 7 days, respectively, at a pulse frequency of 47 kHz, with a power consumption of 549 W in all treatments. Reduction of anthocyanin (cyanidin-3-glucoside (C3G)) after 90 s of exposure	98
Vitamin C	High voltage atmospheric cold plasma	Orange juice	Ambient air and MA65 gas	5-log reduction of *Salmonella enterica* in 25 mL orange juice after 30 seconds of direct or indirect treatment using air or MA65 gas Quality impact was minimal: vitamin C loss was 22% (*vs.* 50% in heat pasteurization)	99
Antioxidant	Atmospheric cold plasma (DBD)	Jujube juice	Ambient air	*Alternaria* mycotoxins; AOH (alternariol): 56.0% reduction and AME (alternariol monomethyl ether): 68.2% reduction) at 30 kV for 2 min and DPPH activity was retained	100
Antioxidant	Atmospheric cold plasma (DBD) and glow discharge plasma	Apple juice	DBD: ambient air Glow discharge: synthetic air	DBD: reduction of POD (−56%) and PPO (−50%) at 50 Hz, 20 kV Glow discharge: 20 mL min^{-1} air plasma for 30 min reduced PPO (−88%) and POD (−43%) Increases antioxidant capacity by 50% in DBD at 50 Hz, 20 kV and 14% in Glow discharge at 10 mL min^{-1} air plasma flow rate for 10 min	101
Antioxidant	Atmospheric cold plasma (DBD)	Banana slices	Ambient air	70% and 100% reduction of polyphenol oxidase and peroxidase enzyme at 6.9 kV for 46 s 50% increase in antioxidant activity	102
Oilseeds					
Seed germination	Computer controlled RF cold plasma (HD-2N)	Soybean	Helium	14.66% increase in seed germination at 13.56 MHz, 80 W for 15 s	103
Seed germination	Computer controlled RF cold plasma (HD-2N)	Rapeseed (Zhongshuang 7 & Zhongshuang 11)	Helium	6.25% and 4.44%, respectively, increase in seed germination at 13.56 MHz, 100 W for 15 s	104
Seed germination	RF cold plasma	Sunflower seed	Partial vacuum air	Treatment increased seed germination rate by 19.9% at 5.28 MHz in air (at a pressure of 200 Pa), and the specific power of 0.35 W cm^{-3}	105

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Specific name	Type of cold plasma	Matrix	Feed gas	Quantitative details	References
Sprout length	DBD for soybean followed by plasma arc discharge for creating plasma activated water from distilled water	Soybean in plasma activated water (PAW) and distilled water (DW)	Ambient air	41.07% (DW) and 31.59% (PAW) (60 s of DBD treatment), 4 days of soaking	106
Extraction efficiency	Atmospheric cold plasma (DBD) as pretreatment during Soxhlet oil extraction	Sesame and sunflower seeds	Oxygen and nitrogen	Increased extraction efficiency of unsaturated fatty acid by 5 and 3.9%, respectively, for sesame and sunflower at 25 kV and 50 Hz for 15 min	107
Cereals					
Protein structure	Atmospheric cold plasma (DBD)	Hard and soft wheat flour	Ambient air (45 ± 1% RH and 20 ± 2 °C)	Maintains β-sheets + antiparallel β-sheets (32.63 and 33.04%, respectively for hard and soft) at 60 kV, 10 min, retaining the orderly structure of protein; however, loss of α-helix (15.7%) and β-turns + β-sheets (14.2%) in hard wheat compared to control	108
Lipid	Continuous cold plasma prototype, DC powered	Wheat dough	Ambient air	100% reduction of oxidatively labile fatty acid and linolenic acid at 9 kHz, 20 V and 0.43 W cm^{-2} for 120 s as evidenced by dose dependent increase of hydroperoxide and *n*-hexanal	109
Stickiness, hardness, and cooking time	RF cold plasma	Parboiled rice	Ambient air	Stickiness of rice increased by 51.1% at 13.56 MHz, 50 W for 15 min, hardness reduced (49.6%), cooking time reduced (44.3%)	110
α-Amylase activity and hardness	Atmospheric cold plasma (DBD)	Brown rice	Ambient air	α-Amylase activity increased (1.21-fold greater than the unexposed controls) and water uptake during soaking increased (5.5 to 8.1%), at 15 kHz, 250 W for 5 min; hardness was reduced up to 104.6 from 116.2 N in 20 min (dose dependent)	111
Cooking time	RF cold plasma	Brown rice	Ambient air (RH 45.3 ± 0.3%, 24 °C)	Decrease in cooking time by 27.5% at 13.56 MHz, 50 W for 10 min	62
Amylose activity	RF cold plasma	Rice starch	Ambient air	Highest leaching of amylose (23% reduction from control) at 13.56 MHz, 60 W for 5 min, followed by 40 W 10 min, 60 W 10 min, and 40 W 5 min	112
Phenolic and flavonoid content	Atmospheric cold plasma (DBD) and vacuum cold plasma	De-oiled rice bran and de-oiled corn bran	Ambient air and vacuum (∼−250 mm Hg), respectively, DBD and vacuum	Increased extraction of phenolic content by 4.7 and 7.1% and flavonoid content by 43.3 and 29.1% at 220 V in DBD and vacuum, respectively, compared to the control in rice bran Phenolic content extraction increased by 37.97 and 28.69% flavanoid by 12.20% and no change in DBD and vacuum, respectively, compared to the control in corn bran	113
Milk and milk proteins					
Foaming capacity	Atmospheric cold plasma (DBD)	Whey protein isolate (WPI)	Ambient air	Foaming capacity increased by 29% at 70 kV, 15 min, compared to the control	114
Particle size	Glow discharge plasma (indirect)	Chocolate milk	Nitrogen	Volume diameter is highest at 18.3 μm (5 min/20 mL min^{-1}) and surface diameter is highest at 15 min/30 mL min^{-1}	115

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Table 1 (*Contd.*)

Specific name	Type of cold plasma	Matrix	Feed gas	Quantitative details	References
Wettability	RF cold plasma (CRPT) and corona plasma discharge (CAPT)	Milk protein concentrates and soy protein isolate	Dry air (99.999%)	Five seconds of CRPT (13.56 MHz) decreased the apparent contact angle from 126 ± 4 to zero degrees (complete wetting) and better than CAPT	116
Denaturation	Micro jet atmospheric cold plasma	Skim milk	N_2–O_2 (0.9 mol N_2 and 0.1 mol O_2 per mol gas) and N_2	N_2–O_2: 71.3% of α-lactalbumin, 57.6% of β-lactoglobulin, and 54.7% of BSA denatured at 5 min. For N_2: β-lactoglobulin, 19.4% denatured at 5 min, followed by α-lactalbumin and then BSA with 9.4% and 5.0%, respectively. (20 kV, 15–25 Hz)	117
Bacterial count	Atmospheric cold plasma (DBD)	Sheep milk	Ambient air	Microbial inactivation rate achieved after 300 s using CP similar to pasteurization at 40 ± 0.25 W of input power Reduction up to 2.98 log CFU mL^{-1} from 4.3 log CFU mL^{-1} (control)	118
Pulses					
Disintegration and encapsulation ratio	Atmospheric cold plasma (DBD)	Red bean seed ferritin (RBF)	Ambient air (50% ± 2% RH at 20 °C ± 1 °C)	Treated ferritin is disintegrated at 4 pH and can be reassembled at 7 pH. Encapsulation ratio of curcumin in the treated RBF reached 12.7% (w/w) at 12 kHz, 60 V, DC powered for 120 s	119
Solubility	Atmospheric cold plasma (DBD)	Peanut protein isolate	Ambient air (50 ± 1% RH and 25 ± 2 °C)	12.7% increase in solubility after 7 min of treatment at 70 V	120
Emulsifying properties	Atmospheric cold plasma (DBD)	Grass pea protein isolate	45 ± 5% (RH) and 25 ± 2 °C	−30.8 mV surface charge at 18.6 kV for 60 s from 22.8 mV in control 25.5% increase in adsorbed protein (%) at 18.6 kV for 60 s from the control	121
Emulsifying property, foaming capacity and allergen	Atmospheric cold plasma (DBD)	Soy protein isolate	Ambient air	Emulsifying (56 to 168%, compared with control) and foaming capacity (60 to 194%) Allergenicity reduced by 75% at 120 Hz for 5 min	122
Water holding capacity	Atmospheric cold plasma (DBD)	Pea protein concentrate (PPC)	Ambient air	85% water holding capacity when the CP treated PPC (10 min, 3500 Hz, 0–30 kV voltage output) was heated at 80 °C	123
Gelling temperature	Atmospheric cold plasma (DBD) followed by pH shifting	Pea protein concentrate	Ambient air	Pretreatment reduced gelling temperature and time (95 °C for 60 min reduced to 70 °C for 10–20 min)	124
MAP condition	Atmospheric cold plasma (DBD)	Soy protein isolate	Ambient air	Primary structure undisturbed When oxygen >40% in MAP, solubility, water holding capacity, gelling, emulsifying and foaming properties were increased	125
Meat and meat products					
Fatty acids	In-package atmospheric cold plasma (DBD)	Mackerel fillets	Ambient air (50% RH and 15 °C)	Palmitic acid reduced by 46%, oleic acid increased by 183% and DHA increased by 9.8% at 80 kV 1 min compared to the control. EPA increased by 233% at 80 kV 5 min	126

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Specific name	Type of cold plasma	Matrix	Feed gas	Quantitative details	References
Gelling ability	Atmospheric cold plasma (DBD)	Pork	Ambient air	Gelling ability reduced from 79.3 to 68.5 °C and from 60.5 to 51.8 °C for pork gelatin treated with plasma at 80 kV for 15 min	127
Protein structure and particle size	High voltage atmospheric cold plasma	Bovine serum albumin	Ambient air and MA	Loss of α-helix from 46 to 19%, and increased particle size from 10 nm to 113 μm in MA treated at 90 kV for 60 min	25
Protein stability	Atmospheric cold plasma (DBD)	Hairtail fish	Ambient air	3 Times higher carbonyl content at 50 kV for 180 s, protein stability reduced based on reduced sulfhydryl content to 0.34 nmol mg^{-1} protein from 0.56 nmol mg^{-1} protein in control at 50 kV for 300 s	128
Microbial synthesized product					
Xanthan gum	Atmospheric cold plasma (DBD)	Xanthan gum	Ambient air	Xanthan gum (60 W – 20 min) showed the highest surface area *i.e.* 46.09 m^2 g^{-1}, while xanthan gum (50 W – 15 min) showed the highest average pore diameter of 44.5247 Å and total pore volume of 0.701 cm^3. Thermal properties unchanged	129
Freshness retention					
Odour activity	Atmospheric cold plasma (DBD	Pineapple juice	Ambient air	Retains freshness and removes off flavours at 50 Hz, 20 kV for 10 min	130
Fermentation activity					
Acid production	In-package atmospheric cold plasma (DBD)	Fermented radish paocai	Ambient air (20 °C and RH of 45%)	Increased total acid production during storage of 7 days by 72.3%. Better than pasteurization (70 °C for 30 min) When treated at 60 kV, 50 Hz for 60 s, three times, and stored for 7 days, LAB was retained and gas producing yeast was not detected	20
Aflatoxin reduction					
Aflatoxin	RF cold plasma	Groundnut	Ambient air	90% reduction of aflatoxin B1 at 13.56 MHz, 60 W for 12 min	131
Antigenicity					
Allergen	High voltage atmospheric cold plasma	Whole peanut (WP) and dry defatted peanut flour (DPF)	Ambient air	Reduction in antigenicity of protein Ara h 1 by 43% in DPF and 9.3% in WP at 80 kV	132
Allergen	High voltage atmospheric cold plasma (large gap pin to plate plasma reactor)	Peanut	Ambient air	Antigenicity for Ara h 1 and Ara h 2 reduced by 65 and 66%, respectively at 52 kHz and a discharge voltage of 32 kV	133
Allergen	Glow discharge (GD) and spark discharge (SD) plasma (tunable)	Milk protein	Ambient air (atmospheric pressure)	Antigenicity reduced by 49.9% and 91.1% (SD (8 kV) and GD (5 kV), respectively) in casein at 25 kHz for 30 min Similarly, 49.5% (SD) and 45.5% (GD) reduction of α-lactalbumin antigenicity	134

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glycosidic bond cleavage, followed by radical recombination to form covalent bonds.[67] While water molecules may be released as by-products during condensation reactions associated with cross-linking, they do not directly mediate the formation of covalent bonds between starch molecules. Overall, cold plasma treatment induces depolymerization, cross-linking, erosion and introduction of new functional groups of starch molecules, impacting their structural, rheological, and functional properties.[68]

5 Applications of cold plasma

Cold plasma has a wide range of applications (Fig. 2). It has been used in food processing, agriculture, food safety, preservation, and other applications such as packaging sterilization, odor removal and air decontamination. The effects of cold plasma on different bacterial strains present in various items are summarized for food safety and preservation in numerous studies.[69,70] Different types of food products *viz.* cereals, pulses, oilseeds, vegetables, milk, and meat were also studied (Table 1). In the following sections, a brief discussion of the applications of cold plasma is also presented.

5.1 Food processing

Cold plasma improves the functional properties of food components.[135] For example, the functionalization (gelatinization and thickening) of wheat, potato, corn, rice and other waxy grains' starch can be modified after cold plasma treatment.[136,137] The reactive species and free radicals generated during plasma can react with starch and modify its cross-linkage, depolymerization, and functionalization. Similarly, cold plasma smoothens the surface of noodles as it facilitates the interaction of gluten and fiber.[138] Plasma can modify the physicochemical and functional properties of proteins as it can unfold and modify the protein structure.[121,139,140] However, with cold plasma treatment, these proteins may be refolded with improved foaming and emulsifying capabilities.[125,141] Using hydrogen-infused cold plasma, partially hydrogenated soybean oil without trans fatty acids was created.[142]

The majority of fruit juice preparations have a cold plasma treatment to increase the amount of nutrients, bioactive substances, and vitamins.[143] However, prolonged cold plasma treatment may have a reverse effect on the amount of nutrients.[144] When compared to other treatments such as the separate usage of US, HVCP, and control therapy, Umair *et al.*[145] found a rise in coloring compounds (pigments), including carotenoids, lycopene, and lutein content, with the combined effect of ultra-sonication (US) and high-voltage cold plasma (HVCP) treatment. Additionally, they discovered that with this method, more chlorogenic acid was present in the carrot juice. Even the sucrose and glucose contents were increased in the carrot juice prepared (Fig. 3).

5.2 Fruits and vegetables

Fresh produce, which may contain pathogens such as *Escherichia coli* and *Listeria monocytogenes*, continues to be the principal source of food-borne diseases.[146] Fresh produce can be

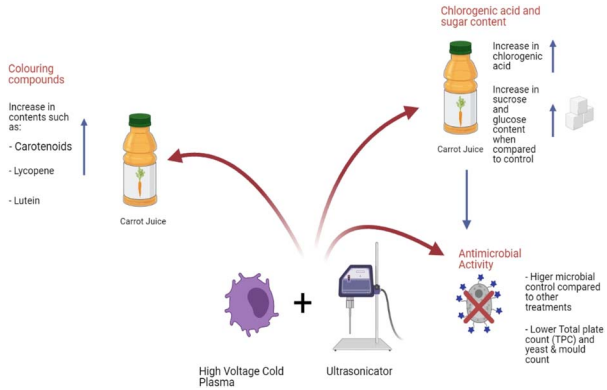

Fig. 3 Advantage of the combined effect of ultra-sonication (US) and high-voltage cold plasma (HVCP) treatment.[145]

effectively controlled from contamination by having post-harvest decontamination treatments.[147] Fruits and vegetables benefit most from non-thermal plasma treatments since they require ambient temperature processing to maintain their safety while minimizing quality loss.[148,149] Fresh produce's bacterial population has been shown to decrease when treatment time and voltage are increased. It has less to no impact on the physical characteristics of color and texture.[150] Plasma discharge arrangement, contamination type, and plasma transfer direction all have a significant impact on how effectively microbes are decontaminated.

A 5.71 log reduction in *E. coli* O157:H7 cells was seen when plants including carrot, lettuce, and cucumber were treated with 400 W cold nitrogen plasma for 2 min and 5% bacteriophage treatment for 30 min.[151] To inactivate *E. coli* DSM 1116, an atmospheric pressure plasma jet was used for 60 s on corn salad, cucumber, apple, and tomato.[152] The plasma source was 5 mm away from the samples with a short treatment time of an initial 20 to 30 s. This arrangement helped to preserve the color and texture of the samples. This proves that a short duration is necessary for cold plasma treatment. Intermittent corona discharge plasma jet (ICDPJ) produced at different input current levels (2.0, 3.0 and 4.0 A) for decontaminating kumquat fruits to reduce the microbial load, ranging from 0.77 to 1.57 CF ml^{-1}.[153] ICDPJ-treated fruits did not change the taste, flavor, color, texture, and total acceptance. Moreover, this method extends the shelf life of the fruits up to 15 days at a storage temperature of 25 °C. Blueberries were subjected to an aerobic cold plasma treatment for less than 60 seconds, which aided to preserve their firmness and phytochemical content for up to 7 days at 4 °C with a 1.5 log reduction in aerobic plate count compared to untreated fruits.[98] A dielectric barrier discharge (DBD) generated gas plasma was directed to the sample surface of fresh-cut melon. This kind of plasma treatment for 15 min on each side of the fresh-cut melon extends the shelf life by 4 days at 10 °C with minor changes in quality parameters.[154] The extended shelf life of the fresh-cut melon was due to the delayed growth of mesophilic and psychrophilic microbes, with inactivation of 17 and 7% of peroxidase and pectin methyl esterase, respectively.

Cold atmospheric plasma fumigation with a minimum of 700 μL L^{-1} for 5 minutes effectively inhibited the development

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of *B. cinerea* both *in vitro* and *in vivo*. The pathogen was subjected to 700 μl L^{-1} and 1000 μl L^{-1} for 5 minutes each in order to uncover the potential mechanism of CAP fumigation's antifungal action. The findings showed that the pathogen's spores treated with CAP experienced cytoplasmic vacuolation, cell membrane breakdown, and shrinking.[155] The MINI ACP system effectively inactivated grain-related fungi such as *Aspergillus fumigatus*, *Fusarium species*, and *Candida albicans* on PDA agar plates, milled rice, paddy rice, and rice bran. The system achieved a 4-log reduction in fungal counts within 2 minutes, with a 5-log reduction observed after longer treatment duration. Reactive oxygen and nitrogen species (ROS and RNS) generated by the plasma disrupted fungal cell membranes and proteins, resulting in effective fungal inactivation.[156] According to Zhai *et al.*, *P. expansum* spores in sterile distilled water and kiwi fruit juice were reduced by around 6-log after DBD plasma treatment at 18 kV for 240 s.[157] The plasma source was 5 mm away from the samples with a short treatment time of an initial 20 to 30 s. This arrangement helped to preserve the colour and texture of the samples. This proves that a short duration is necessary for cold plasma treatment. Intermittent corona discharge plasma jet (ICDPJ) produced at different input current levels (2.0, 3.0 and 4.0 A) for decontaminating kumquat fruits to reduce the microbial load, ranging from 0.77 to 1.57 CF ml^{-1}.[153] ICDPJ-treated fruit did not change the taste, flavour, colour, texture, and total acceptance. Moreover, this method extends the shelf life of the fruits up to 15 days at a storage temperature of 25 °C. Blueberries were subjected to an aerobic cold plasma treatment for less than 60 s, which aided to preserve their firmness and phytochemical content for up to 7 days at 4 °C with a 1.5 log reduction in aerobic plate count compared to untreated fruits.[98] A dielectric barrier discharge (DBD) generated gas plasma was directed to the sample surface of fresh-cut melon. This kind of plasma treatment for 15 minutes on each side of the fresh-cut melon extends the shelf life by 4 days at 10 °C with minor changes in quality parameters.[154] The extended shelf life of the fresh-cut melon was due to the delayed growth of mesophilic and psychrophilic microbes, with inactivation of 17 and 7% of peroxidase and pectin methyl esterase, respectively. It also inactivates other fungal organisms, such as *Penicillium* and *Botrytis*, in fruits and vegetables.[158,159]

5.3 Dairy products

Due to its high nutritional density, milk is particularly prone to microbial deterioration.[160] Pathogenic bacteria have been managed by thermal methods in raw milk.[161] However, the nutritional value and organoleptic qualities of dairy foods are altered by these processes.[162] Non-thermal plasma treatment has been investigated with the hope that it can reduce microbial load while protecting the distinctive nutrients and flavors of milk. A study carried out illustrated that milk inoculated with *E. coli* and *Listeria* subjected to non-thermal plasma treatment achieved a 2 log10–3 log10 reduction without any changes to the appearance of the product.[163] Existing literature suggests that non-thermal plasma can preserve the sensory and nutritional qualities of various dairy products, indicating a potential minimal impact on milk's nutritional content.[164] In-package cold plasma treatment for sliced cheese has also been explored. Yong *et al.*[165] reported that this process achieved a 2.88 log10–3.11 log10 reduction of *E. coli* and *Listeria* after 15 min of cold plasma treatment, proving its effectiveness.

5.4 Meat and meat products

Meat is highly susceptible to microbial contamination, posing risks from pathogens such as *Salmonella* spp. and *Escherichia coli*, which can cause severe foodborne illnesses.[166,167] To meet increasing consumer demands for safe, high-quality meat products, advanced technologies such as cold plasma activated water have been explored for their antimicrobial efficacy.[168] For instance, in-package cold plasma treatment has been shown to inactivate *Listeria* and *Escherichia coli*, achieving reductions of 2.04 to 2.54 log_{10} CFU.[169] Additionally, studies report minimal changes in meat texture and color following plasma treatment, with treated chicken exhibiting shelf life extensions of up to 14 days.[170]

However, it is important to note that cold plasma treatment can also induce physicochemical changes in meat. Reactive oxygen and nitrogen species (RONS) generated during plasma exposure can accelerate the oxidation of myoglobin, leading to increased metmyoglobin formation and browning discoloration.[171] In addition, reactive oxygen species (ROS) attack the polyunsaturated fatty acids in meat, triggering lipid peroxidation and the formation of volatile aldehydes, which contribute to off-flavors and sensory deterioration[172,173] These effects underline the necessity of optimizing plasma treatment parameters to balance microbial safety with preservation of sensory and quality attributes.

5.5 Grain germination

Ongoing research aims to develop a technology that increases seed germination effectiveness.[174] Several technologies, including ultrasonic and magnetic field treatments, have been explored for seed germination. However, non-thermal plasma technology has been observed to have a favorable impact on seed germination.[175] The permeability, germination rate, and yield of the surface have all increased as a result of the cold plasma treatment. A speedier germination process is aided by the seed surface's increased permeability. A study showed that after non-thermal plasma treatment, this approach led to 1.6 times longer root and stem development in radish sprout seeds.[176]

Another study using this method revealed that treated tomato seeds sprouted 32.7% more often than untreated tomato seeds. The germination start time was also shortened, and seeds treated with a non-thermal plasma produced tomatoes with yields that were 20% higher.[177] As reported by Bezerra *et al.*,[178] cold plasma treatment can be used to influence cooking factors, such as reduction in cooking time, improvement in texture, and nutritional value of various food products, in addition to improving germination and other growth metrics. Studies have also shown a bright future for non-thermal plasma technology in removing hazardous chemicals from food goods.[179] Cold plasma treatment is not only for the elimination of chemical residues but may also be used to treat naturally

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occurring plant components that, when heated, generate complex molecules that are difficult for the digestive system to digest.[180] A promising solution to address these issues in the food-processing sector is non-thermal plasma therapy.

5.6 Wastewater treatment

Water is used in the food processing sector for equipment cleaning, steaming, washing, and processing, as well as food preparation.[181] As a result, waste and discharge from food processing facilities contain a lot of organic compounds. Nutrient-rich wastewater from food processing facilities might cause disease outbreaks if it is not handled properly. Reactive species are ideal for the food processing industry since they can be employed by a variety of industries for decontamination and the degradation of chemicals from water.[182] Plasma treatments have been proven to be successful at removing color and contaminants from water.[183] Due to technology's beneficial effects, there is a significant demand for technology that is effectively scaled up with equipment that is specially made for the food processing industry to handle large-scale waste disposal.[35,184]

Cold plasma technology produces reactive oxygen and nitrogen species, including $HO^{\bullet}$, $O^{\bullet}$, $HO_2^{\bullet}$, O_3, H_2O_2, ultraviolet light, heat, and shockwaves. These highly reactive species facilitate the efficient removal of recalcitrant contaminants under ambient conditions. The hydroxyl radical ($HO^{\bullet}$), in particular, is a strong, non-selective oxidant that may break down pollutants quickly. Its effectiveness is increased when paired with plasma-induced physical processes such as shockwave and UV radiation.[185] Plasma treatments have been proven to be successful at removing color and contaminants from water.[183] Combining slug flow plasma technology with gas/liquid discharge plasma under pressured argon created a continuous reaction field in the gas/liquid discharge plasma environment under high pressure. The rate of dye decomposition reduced as system pressure increased when the system was used to break down methylene blue (MB).[186] A multi-hole DBD plasma-based AOP system was used to treat the methylene blue and methyl orange (MO) solutions. As the reaction continued, the solutions gradually clarified (color faded), suggesting a definite drop in the MB and MO concentrations. MO was broken down into two structures (SO_3 and phenylsulfinate ions) by oxidation *via* $^{\bullet}OH$, which also breaks the –N–N– double bond, resulting in its degradation. The original structures are changed into CO_2, H_2O, Cl^-, SO_4^{2-}, and NO_3 *via* MO degradation.[187] Due to technology's beneficial effects, there is a significant demand for technology that is effectively scaled up with equipment that is specially made for the food processing industry to handle large-scale waste disposal.[35,184]

5.7 Food safety and preservation

Cold plasma rendered inactive common foodborne pathogens such as *E. coli*, *Listeria monocytogenes*, and *Salmonella* spp.[188,189] The active species of cold plasma act on the cell membrane's lipoproteins and peptidoglycans, causing Gram-negative bacteria to leak and resulting in intracellular DNA damage. While there was no cell leakage in Gram-positive bacteria, internal components were harmed. Since the free radicals produced by the cold plasma treatment may disrupt several layers of bacterial spores before reaching the core, the bacterial spores are also impacted.[23,190] In a non-thermal processing method known as high microwave density cold plasma treatment (HMCPT), *B. cereus*, *A. brasiliensis*, and *E. coli* O157:H7 cells' starting counts were decreased, and their proliferation in the onion powder was inhibited.[191] The exposure of cold plasma rendered inactive the enzymes that prevent food preservation, such as polyphenol oxidase, peroxidase, lipase, dehydrogenase, trypsin, chymotrypsin, pectin methyl esterase, superoxide dismutase, lipoxygenase, amylase, and alkaline phosphatase.[78]

5.8 In-package cold plasma systems

The food item is sealed in a plastic wrapping for in-package cold plasma treatment.[192,193] The idea behind in-package cold plasma treatment is to place gaseous disinfectants where they can come into contact with the food.[194] A customized gas mixture or room air may serve as the gas inside the package.[195] When the gas is briefly exposed to a high electric field, breakdown of the gas happens.[16] As a sterilizing agent for the food product enclosed in the packaging, the ionized condition of the gas, or plasma, aids in microbial inactivation without compromising the integrity of the packaging materials. This procedure effectively eliminates a sizable population of spoilage bacteria while beginning with a known gas mixture and ending with the same gas mixture.[193] Cold plasma quickly diffuses around the packing due to its high diffusivity coefficients, ensuring consistent treatment. Depending on the species, package type, volume, humidity, light, and initial concentration of each microbe present in the packaging, any unreacted cold plasma will spontaneously recombine to produce the original gas existing within the packing.

Over the past few years, a variety of engineering concepts for producing cold plasma discharges inside enclosed containers have emerged. The three distinguished treatments among these newly developed techniques include volumetric dielectric barrier discharge plasma,[196] surface dielectric barrier discharge cold plasma inside the package (Feizollahi *et al.*[197]) and the on-package surface dielectric barrier discharge cold plasma.[198] The operating voltage, frequency, and electrode location of these three approaches differ. In order to create a dielectric barrier discharge plasma, extremely high voltages must be applied throughout the entire package. Dielectric barrier discharge can be used at higher frequencies for in-package decontamination. The degree of ionization and, consequently, the quantity of reactive species present are constrained by the comparatively low voltages and high frequencies used in surface dielectric barrier discharge procedures. Ionization mostly takes place at the surface when the surface dielectric barrier discharge cold plasma is deposited inside the container (Fig. 4). Due to this, it is more difficult to reach the appropriate level of microbial inactivation and requires prolonged treatment periods. When in-package cold plasma is used on food products, antimicrobial species develop inside the sealed packaging, eliminating any safety concerns related to handling issues that could otherwise

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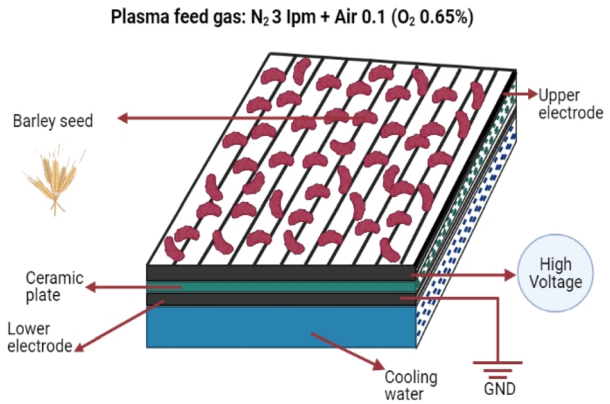

Fig. 4 Surface dielectric barrier discharge plasma treatment.[199]

limit its use. Numerous benefits may result from the removal of germs from foods as they are packaged. By using in-package cold plasma treatment, the danger of post-process contamination by pathogenic agents and external food spoiling can be decreased. This process also permits the use of a range of packaging materials and altered gas atmospheres, as well as direct freezing, refrigeration, or storage at ambient temperature. A sustained release of antimicrobial-enhancing substances from the surrounding packing material can also result from in-package cold plasma therapy.

5.9 In-package decontamination

Numerous pathogens and spoilage germs have been rendered inactive by plasma treatments when applied to fruits, vegetables, dairy products, eggs, meat, and meat products.[85] Major food-borne outbreaks have been linked to *Salmonella*, *Campylobacter*, *E. coli*, and *Listeria monocytogenes* contamination; as a result, much research has concentrated on inactivating these pathogens *via* non-thermal plasma treatments.[200] Although generalizations for an effective method of inactivating various pathogens have been made, they are not directly comparable to one another due to differences in plasma sources and process factors. Surface dielectric barrier discharge cold plasma is a treatment used to achieve these sterilization aims.[201]

In-package cold plasma sources have been used in model plasma experiments to cleanse bacteria, yeast, spores, and toxins.[202,203] These in-package non-thermal plasma systems have been shown in numerous investigations to enable the reduction of *E. coli*, *Listeria*, and *S. aureus* to undetectable numbers.[204] Numerous studies have shown that non-thermal plasma treatments can effectively inactivate germs, bacterial spores, and biofilms.[39,205,206] It was discovered that the length of post-treatment storage needs can determine the degree of microbial inactivation.[70,96,207]

6 Comparison with non-thermal technologies

Cold plasma technology, high-pressure processing (HPP), pulsed light (PL), and ultrasonic treatment (UT) each offer distinct advantages and limitations in non-thermal food processing. Cold plasma is highly effective for surface decontamination with minimal impact on food quality, such as reducing *E. coli* on spinach by 3–4 log CFU g^{-1} within 5 min, but it faces challenges with high energy consumption (0.5 to 2 kWh per kg) and scalability issues.[208,209] HPP excels in maintaining food quality and texture, achieving significant microbial reductions, such as a 5-log reduction in *Listeria* in ready-to-eat meats, though it requires substantial investment and energy (1.5 to 3 kWh per kg).[210,211] PL provides efficient surface decontamination with moderate costs and energy use (0.1 to 0.3 kWh per kg), effectively reducing *Salmonella* on almonds by 3–4 log CFU g^{-1}, but can cause surface discoloration.[212,213] UT is versatile and cost-effective, enhancing the extraction of bioactive compounds with moderate energy consumption, though its efficacy improves when combined with other treatments.[214,215] Thus, while cold plasma is advantageous for surface applications with minimal quality impact, its broader adoption hinges on advancements in energy efficiency and scalability compared to the established HPP and the efficient PL and UT methods.

7 Safety and by-products of cold plasma technology in food science

Cold plasma technology involves the use of ionized gas, known as plasma, at or near room temperature to achieve microbial decontamination, enhance shelf life, and maintain the sensory and nutritional quality of food products. Despite its numerous advantages, it is essential to thoroughly understand the safety implications and by-products associated with cold plasma treatment to ensure its optimal and safe application in the food industry.

7.1 By-products of cold plasma treatment

Cold plasma generates a variety of reactive species, including reactive oxygen species (ROS) such as ozone, hydroxyl radicals, and hydrogen peroxide, as well as reactive nitrogen species (RNS) such as nitric oxide and nitrogen dioxide. These species play a crucial role in the antimicrobial action of cold plasma, effectively inactivating bacteria, viruses, and fungi by disrupting cell walls and interfering with cellular functions. The interaction of these reactive species with food components can lead to the formation of secondary by-products. For instance, the treatment of food containing lipids can result in the generation of lipid oxidation products, which may affect the quality and safety of the food. Additionally, cold plasma can induce changes in protein structures, resulting in modified proteins that may have altered functional properties or immunogenic potential.[216]

7.2 Adverse effects of cold plasma

While cold plasma technology offers significant benefits, there are potential adverse effects that need to be considered.

7.2.1 Fat oxidation and deterioration. One of the primary concerns with cold plasma treatment is the oxidation of lipids. The reactive species generated can initiate lipid peroxidation,

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leading to the formation of primary oxidation products such as hydroperoxides and secondary oxidation products such as aldehydes and ketones. These compounds can negatively affect the sensory attributes of food, causing rancidity and off-flavors. Moreover, lipid oxidation can reduce the nutritional quality of food by degrading essential fatty acids and fat-soluble vitamins.[127]

7.2.2 Taste changes. The interaction of reactive species with food matrices can also lead to alterations in taste and flavor profiles. For example, the oxidation of fatty acids and amino acids can produce volatile compounds that may impart undesirable flavors to the food. This can be particularly problematic in foods with delicate flavors, where even minor changes can significantly affect consumer acceptance.[135]

7.2.3 Production of harmful substances. There is a possibility that cold plasma treatment could lead to the formation of potentially harmful substances. For instance, nitrogen-containing reactive species can react with organic molecules to form nitrosamines, which are known to be carcinogenic. Additionally, the formation of acrylamide, a compound with potential health risks, can be catalyzed by the reactive species in foods containing reducing sugars and amino acids.[217]

7.3 Ensuring safe application

To soften these adverse effects, it is crucial to optimize the parameters of cold plasma treatment, such as the type of gas used, exposure time, and intensity. Researchers are actively investigating the mechanisms of reactive species interaction with food components to better understand and control the formation of undesirable by-products. Moreover, integrating cold plasma technology with other preservation methods, such as vacuum packaging or antioxidant application, can help minimize the negative impacts on food quality.[39]

8 Large scale commercial applications

Cold plasma technology, an advanced non-thermal method for food processing, has broad application prospects that are contingent on several factors, including economic and technical feasibility, cost considerations, equipment design, energy efficiency, and environmental protection effects. This discussion explores these aspects in detail to provide a comprehensive understanding of the viability of cold plasma technology for large-scale commercial applications. The initial investment in cold plasma technology can be substantial due to the need for specialized equipment and installation. However, when considering long-term benefits such as reduced spoilage, extended shelf life, and decreased reliance on chemical preservatives, the overall cost-effectiveness becomes more apparent. Additionally, improvements in technology and economies of scale are expected to lower the cost of equipment and operational expenses over time.[77] The operational costs of cold plasma systems are influenced by factors such as energy consumption, maintenance, and consumables (*e.g.*, gases used to generate plasma). While the energy requirements of cold plasma systems are relatively low compared to thermal processing methods, continuous operation and scaling up for large-scale applications require careful management to maintain cost efficiency. The growing consumer demand for minimally processed, chemical-free food products provides a strong market incentive for adopting cold plasma technology. By enhancing food safety and quality without compromising nutritional value, cold plasma-treated products can command a premium price, thereby offsetting initial and operational costs.[13]

The design of cold plasma equipment plays a crucial role in its feasibility for large-scale applications. Scalable systems that can handle varying volumes of food products efficiently are essential. Modular designs that allow for easy integration into existing processing lines can also enhance the adoption of this technology. In addition, user-friendly interfaces and automated controls can simplify operation and maintenance, reducing the need for specialized labor. Cold plasma technology is generally energy-efficient, utilizing low power to generate plasma. The energy efficiency of the system depends on the type of plasma generator used (*e.g.*, dielectric barrier discharge, atmospheric pressure plasma jet) and the operational parameters. Innovations in plasma generation and power supply design continue to improve energy efficiency, making the technology more attractive for commercial use.[188]

Optimizing process parameters such as treatment time, plasma intensity, and gas composition is critical to achieving desired outcomes without compromising food quality. Advances in computational modelling and real-time monitoring technologies aid in fine-tuning these parameters, ensuring consistent and effective treatment in large-scale operations. One of the most significant environmental benefits of cold plasma technology is the reduction in the use of chemical preservatives and sanitizers. This not only minimizes the chemical residues in food products but also reduces the environmental impact associated with the production, use, and disposal of these chemicals. Cold plasma processing generally operates at or near room temperature, resulting in lower energy consumption compared to traditional thermal processing methods. This contributes to a lower carbon footprint, aligning with sustainability goals and regulations aimed at reducing greenhouse gas emissions in the food industry. Enhanced microbial safety and extended shelf life contribute to reduced food waste, which has significant environmental and economic implications. By preventing spoilage and extending the usability of food products, cold plasma technology supports waste minimization efforts and promotes sustainable food systems.[218]

9 Challenges and limitations

Cold plasma technology has shown great potential in various applications, including sterilization, surface modification, and agriculture. However, there are significant challenges related to energy consumption, scalability of the equipment, and long-term stability. Here we discuss these challenges in detail and propose possible solutions to enhance system efficiency and

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broaden its application scope. One of the major challenges is energy consumption; cold plasma generation requires a significant amount of energy, which can be a major limiting factor for its widespread adoption. The process involves ionizing gas molecules, which inherently demands high power input, which is rectified by energy-efficient power supplies. Developing advanced power supplies that optimize energy use can significantly reduce consumption. For instance, utilizing pulsed power supplies instead of continuous wave supplies can enhance energy efficiency by delivering energy in controlled bursts, thereby reducing overall consumption. Using gas mixtures that ionize more easily can lower the energy required to generate plasma. For example, incorporating noble gases such as helium or argon can reduce the ionization threshold, thereby minimizing energy needs. Implementing sophisticated control systems that precisely regulate plasma parameters such as voltage, frequency, and gas flow can help maintain optimal conditions with minimal energy expenditure.[219]

Scaling up cold plasma equipment for industrial applications presents significant engineering challenges. Large-scale systems need to maintain uniform plasma distribution and consistent performance, which can be difficult to achieve. Developing modular plasma systems that can be easily scaled by adding more units can address scalability issues. Each module would operate independently, allowing for uniform plasma generation across larger surfaces. Employing technologies such as multi-electrode systems and advanced reactor designs can help achieve uniform plasma distribution. For example, dielectric barrier discharge (DBD) reactors can be designed with multiple electrodes to ensure even plasma spread. Designing high-throughput systems that can process larger volumes of materials simultaneously can improve scalability. This involves optimizing the reactor geometry and gas flow dynamics to handle higher capacities without compromising performance.[220]

Ensuring the long-term stability of cold plasma systems is crucial for their reliability and practical application. Factors such as electrode degradation, gas contamination, and component wear can affect stability. Utilizing high-performance materials that resist wear and degradation can enhance the longevity of plasma systems. For instance, electrodes made from materials such as tungsten or coated with protective layers can withstand harsh plasma environments. Implementing regular maintenance schedules and real-time monitoring systems can help detect and address issues before they affect system stability. Sensors and diagnostic tools can provide valuable data on system health, allowing for proactive maintenance. Researching and developing self-healing materials that can recover from minor damages automatically can significantly improve the long-term stability of plasma systems. These materials can repair surface cracks or wear, extending the operational life of the equipment.[121]

10 Future directions

The future direction of cold plasma technology in the food industry is set to be transformative, driven by continuous advancements and expanding research efforts. Technology upgrade paths will likely focus on enhancing the efficiency and scalability of plasma systems, with innovations in plasma generation methods and energy optimization playing pivotal roles. Future designs may incorporate more sophisticated control systems and real-time monitoring capabilities to ensure precise and uniform treatment of various food products. Research focuses will encompass understanding the interactions between plasma reactive species and different food matrices at the molecular level, aimed at minimizing any adverse effects on food quality. Additionally, developing integrated systems that combine cold plasma with other preservation technologies, such as modified atmosphere packaging, will be a key area of exploration. There is also potential for extensive studies on the long-term effects of cold plasma-treated foods on human health and nutrition, as well as their environmental impacts, to ensure sustainable and safe food processing practices. As consumer demand for natural and minimally processed foods grows, cold plasma technology is poised to become a cornerstone of innovative food safety and preservation strategies.

11 Conclusions

In conclusion, non-thermal plasma technology, particularly cold plasma, emerges as a promising solution in the food-processing sector for addressing the increasing concerns of food-related allergies, toxins, and microbial contamination. Its application has shown efficacy in altering the allergenicity of proteins, reducing the presence of carcinogenic compounds such as aflatoxins, and enhancing food safety without compromising nutritional integrity. However, the potential of cold plasma extends beyond mere safety enhancements. Its ability to deactivate enzymes, alter the structure and function of starches, and retain micronutrients highlights its utility in improving food quality and fortification. Moreover, cold plasma's role in wastewater treatment and seed germination underscores its broader environmental benefits. Despite these advantages, the technology is not without its challenges. Issues such as lipid oxidation, flavour alteration, and the formation of potentially harmful compounds during plasma treatment necessitate further research to optimize safety protocols and methodologies. Future work should focus on refining plasma treatment processes to mitigate these adverse effects while maximizing their benefits. This includes developing standardized safety parameters, understanding the complex interactions between plasma and various food components, and exploring the technology's application across different food types. As such, non-thermal plasma technology holds significant promise for revolutionizing food processing, ensuring safety and quality, and addressing some of the pressing challenges in food science and technology. This review differentiates itself in that it offers a comprehensive examination of cold plasma applications for both functional uses in food systems and microbiological cleansing, providing useful insights and scientific clarity by combining quantitative results and mechanistic insights. Ongoing research and

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technological advancements are critical to ensuring that this innovative approach can be applied safely and effectively in the food industry. By addressing the challenges associated with fat oxidation, taste changes, and the formation of harmful substances, cold plasma can become a valuable tool for food processing and preservation.

Data availability

No new data were generated or analysed in this study. All data discussed are cited from published literature and are available in the public domain.

Author contributions

Raju Sasikumar: conceptualization, investigation, data curation; Selva Kumar T.: writing – original draft preparation, review & editing; G. Kaviarasu: writing – original draft preparation; Irengbam Barun Mangang: writing – original draft preparation; Ravinder Kaushik: investigation, data curation; Paul Mansingh: writing – original draft preparation, review & editing; Vidisha Tomer: investigation, data curation; Amit K. Jaiswal: conceptualization, writing – original draft preparation, review & editing and supervision.

Conflicts of interest

The authors have declared no conflicts of interest for this article.

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