# Sustainable Cold Plasma Innovations in Food Processing and Preservation: A Next-Generation Approach to Safety and Quality

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**Abstract:**
The increasing demand for safe, minimally processed, and nutritionally superior foods has accelerated the exploration of non-thermal technologies as sustainable alternatives to conventional thermal preservation methods. Among these, cold plasma (CP) has emerged as a next-generation innovation capable of achieving microbial inactivation and enzyme control at ambient temperatures with minimal nutrient degradation. Cold plasma refers to a partially ionized gas comprising reactive oxygen and nitrogen species (RONS), UV photons, electrons, and metastable molecules that collectively induce complex biochemical interactions on food surfaces. These interactions disrupt microbial membranes, denature enzymes, and modify chemical residues, thereby enhancing food safety and extending shelf life without compromising sensory attributes. The technology has demonstrated broad applicability across food matrices—including fruits, vegetables, cereals, meats, dairy, and ready-to-eat products—effectively reducing bacterial, fungal, and viral contaminants. Moreover, CP offers unique advantages for enzyme inactivation, pesticide degradation, and surface sterilization of food contact materials and packaging.

Recent research highlights the synergy between cold plasma and complementary mild treatments such as pulsed electric fields, ultrasound, or natural antimicrobials, forming multi-hurdle strategies for enhanced preservation efficiency. However, successful industrial adoption requires addressing challenges related to treatment uniformity, scalability, regulatory approval, and material compatibility. Advanced reactor designs—such as dielectric barrier discharge (DBD), plasma jets, and gliding arcs—combined with optimized process control using artificial intelligence and real-time plasma diagnostics, are paving the way for smart, adaptable preservation systems. Furthermore, plasma-functionalized packaging materials and in-package plasma sterilization represent promising integrations for eco-efficient processing. This review consolidates the current state of knowledge on cold plasma fundamentals, decontamination mechanisms, impacts on food quality and nutrition, and emerging technological developments, while outlining key research and regulatory priorities for its sustainable implementation in the global food industry.

**Keywords:** Cold-plasma technology, non-thermal food processing, Microbial decontamination, Food quality and shelf-life extension, Plama-food interactions and sustainable food preservation.

## 1.Introduction:

The increasing global emphasis on food safety, sustainability, and nutritional integrity has accelerated the development of novel non-thermal technologies that can minimize energy consumption and preserve product quality. Conventional preservation techniques such as pasteurization, sterilization, and chemical sanitization often lead to undesirable changes in food texture, flavor, and nutrient content, creating demand for milder, eco-efficient alternatives (Chemat et al., 2017). Among the emerging solutions, cold plasma (CP)—a partially ionized gas generated at atmospheric or low pressures—has gained remarkable attention as a sustainable and effective tool for food decontamination and quality improvement (Misra et al., 2019; Pankaj et al., 2021). Cold plasma, also referred to as non-thermal plasma, comprises a complex mixture of energetic electrons, ions, reactive oxygen and nitrogen species (RONS), ultraviolet (UV) photons, and neutral gas molecules (Niemira, 2012). Unlike traditional thermal processing, CP operates at near-ambient temperatures, allowing microbial inactivation without significant heating or loss of sensory quality (Laroussi, 2018). The reactive species generated during plasma discharge attack microbial cell membranes, DNA, and enzymes, leading to rapid decontamination of pathogens such as *Escherichia coli*, *Listeria monocytogenes*, and *Salmonella* on various food surfaces (Thirumdas et al., 2020; Kim et al., 2020). Moreover, the tunability of plasma—by controlling feed gas composition, voltage, humidity, and exposure time—makes it adaptable to diverse food matrices including fruits, vegetables, meat, seafood, and dairy (Surowsky et al., 2016; Bourke & Keener, 2022). The application potential of CP spans across microbial decontamination, enzyme inactivation, pesticide degradation, and toxin neutralization, providing a holistic solution for enhancing food safety (Tolouie et al., 2018; Sakai et al., 2023). In the context of fresh produce, plasma treatment effectively reduces surface pathogens while maintaining firmness, color, and vitamin retention (Kim et al., 2020). In meat and seafood, plasma serves as a clean, chemical-free disinfection method that preserves pigment and minimizes lipid oxidation (Danilova et al., 2022). In liquid foods such as milk and juices, plasma-assisted pasteurization eliminates microbial contaminants with minimal thermal damage, offering an alternative to traditional heat treatments (Misra et al., 2021). Furthermore, recent advancements in in-package plasma systems enable sterilization of sealed foods, thereby preventing post-processing contamination and extending product shelf life (Arjmand et al., 2024). Cold plasma's environmental sustainability also aligns strongly with the United Nations Sustainable Development Goals (SDGs), particularly those targeting good health, clean energy, and responsible consumption. The process is resource-efficient, requiring less water and energy compared to conventional sanitization techniques, while leaving minimal chemical residues (FAO, 2022). From a materials perspective, CP has shown potential in modifying the surface properties of biodegradable polymers used in food packaging. Plasma-treated films based on chitosan, starch, or polylactic acid exhibit enhanced wettability, adhesion, and antimicrobial properties, paving the way for active and intelligent packaging systems that can monitor or respond to food quality changes (Bhatia et al., 2021; Kumar et al., 2022; Agarwal et al., 2023). Despite these promising developments, scaling cold plasma for industrial food processing remains challenging. Issues such as treatment uniformity, energy efficiency, and potential oxidative degradation of sensitive food components must be carefully addressed (Dobrynin et al., 2021). Furthermore, toxicological evaluations and consumer safety assessments are crucial to ensure regulatory acceptance of plasma-treated foods (EFSA, 2021). The absence of globally harmonized standards and guidelines continues to hinder commercialization (Liao et al., 2024). Emerging research trends indicate a shift toward hybrid technologies, where cold plasma is integrated with pulsed electric fields (PEF), UV-C light, ultrasound, or mild heating to achieve synergistic microbial inactivation and quality enhancement (Martillanes et al., 2022). Additionally, integrating artificial intelligence (AI) and Internet of Things (IoT)-based process monitoring systems into plasma reactors is enhancing real-time control of discharge parameters, ensuring consistency and energy optimization (Xia et al., 2023). These developments represent the transition toward next-generation plasma systems, characterized by smart automation, sustainability, and high throughput. This review provides a comprehensive synthesis of cold plasma technology as a transformative innovation in food processing and preservation. It discusses the fundamental plasma generation mechanisms, physicochemical interactions with food systems, microbial inactivation pathways, and effects on nutritional, sensory, and structural properties. Additionally, the review highlights advances in plasma-assisted packaging, regulatory challenges, and future prospects for industrial deployment. Overall, cold plasma represents a next-generation, eco-friendly preservation technology capable of enhancing global food safety, extending shelf life, and supporting the sustainable transformation of the food industry.

## 2. Fundamentals of Cold Plasma: Physics, Chemistry, and Generation Systems:

Cold plasma (CP) is a partially ionized gas that contains a complex mixture of electrons, ions, radicals, neutral atoms, molecules, ultraviolet photons, and metastable species. The plasma state represents the fourth state of matter, distinct from solids, liquids, and gases, and it is generated when sufficient energy is supplied to a gas to cause ionization (Laroussi, 2018). Unlike high-temperature plasmas used in welding or fusion, cold or non-thermal plasma operates at near-ambient temperatures, where the electron temperature (~1–10 eV) is significantly higher than that of heavy species such as ions and neutrals (Misra et al., 2019). This non-equilibrium characteristic makes CP uniquely suited for biological and food applications, as it can inactivate microorganisms and modify surfaces without damaging heat-sensitive components (Niemira, 2012; Bourke & Keener, 2022).

### 2.1 Plasma Physics and Composition:

At its core, plasma formation involves energy transfer from an external electric field to a working gas, resulting in the generation of reactive oxygen and nitrogen species (RONS). The gas becomes partially ionized when free electrons, accelerated by the electric field, collide with neutral gas molecules, causing ionization, excitation, and dissociation events (Thirumdas et al., 2020). The resulting mixture includes reactive species such as atomic oxygen (O), ozone ($O_3$), hydroxyl radicals (•OH), hydrogen peroxide ($H_2O_2$), nitric oxide (NO), nitrogen dioxide ($NO_2$), and peroxynitrite ($ONOO^-$) (Tolouie et al., 2018). These RONS are largely responsible for microbial inactivation and surface oxidation during plasma treatment (Misra et al., 2021). Cold plasma can be generated in different gaseous environments, including air, oxygen, nitrogen, argon, or their mixtures, depending on the desired application. The feed gas composition influences both the type and concentration of reactive species produced. For instance, oxygen-based plasmas tend to yield higher oxidative radicals like •OH and $O_3$, effective against cell membranes and biofilms (Laroussi, 2018), while nitrogen-based plasmas favor NO and $NO_2$ species, which are beneficial for modifying food pigment properties and reducing nitrite requirements in cured meats (Danilova et al., 2022). Argon, a noble gas, is frequently used to stabilize plasma discharge, providing a uniform, low-temperature environment (Surowsky et al., 2016).

### 2.2 Plasma–Food Interactions and Chemical Mechanisms

The antimicrobial and modification effects of cold plasma arise from multi-modal interactions involving physical bombardment, chemical oxidation, UV radiation, and local electric field effects (Pankaj et al., 2021). Reactive species generated in plasma can interact with microbial cells, lipids, proteins, and polysaccharides at the food surface, initiating oxidative stress and structural damage (Thirumdas et al., 2020). For microorganisms, RONS disrupt cell membranes by peroxidizing lipids and oxidizing thiol-containing proteins, leading to leakage of intracellular contents and enzyme inactivation (Niemira, 2012). Reactive nitrogen species such as NO and $ONOO^-$ can modify nucleic acids through nitrosative stress, impairing replication (Laroussi, 2018). Moreover, the UV photons produced during plasma discharge can cause thymine dimerization, contributing to DNA damage in pathogens (Misra et al., 2019). In food matrices, these reactive processes can influence nutritional and sensory attributes. For example, hydroxyl radicals and ozone can oxidize polyphenols and carotenoids, leading to minor pigment changes (Misra et al., 2021). However, when plasma exposure is optimized, degradation can be minimized, and beneficial modifications—such as increased extractability of antioxidants or improved functional properties of proteins—can occur (Tolouie et al., 2018; Thirumdas et al., 2020). In starch-based systems, CP has been reported to enhance hydrophilicity, gelatinization temperature, and film-forming properties (Bhatia et al., 2021).

### 2.3 Plasma Generation Systems

Cold plasma systems are broadly categorized into low-pressure (vacuum-based) and atmospheric-pressure configurations, each with distinct design principles and applications (Bourke & Keener, 2022).

#### 2.3.1 Dielectric Barrier Discharge (DBD):

DBD systems consist of two electrodes separated by at least one dielectric barrier, with a gas (usually air, $O_2$, or $N_2$) flowing between them. When an alternating high voltage is applied, micro-discharges form across the gap, generating plasma at atmospheric pressure. DBDs are commonly used for surface decontamination of solid foods such as fruits, nuts, and meat (Pankaj et al., 2021). The presence of the dielectric prevents arcing, ensuring a uniform and controllable discharge.

#### 2.3.2 Plasma Jets (APPJ):

Atmospheric pressure plasma jets are produced when a feed gas (e.g., He, Ar, or $N_2$) is ionized and expelled through a nozzle as a visible jet of reactive species. APPJ devices are portable and flexible, making them suitable for treating irregular surfaces or packaged foods (Surowsky et al., 2016; Misra et al., 2019). The reactive zone is small and localized, allowing precise treatment with minimal energy.

#### 2.3.3 Gliding Arc Discharge (GAD):

In this system, an electric arc glides along diverging electrodes as the gas flow pushes it downstream, creating a longer discharge region. GAD systems are efficient for large-scale gas treatments and have been explored for bulk sterilization of grains and cereals (Bourke & Keener, 2022).

#### 2.3.4 **Corona Discharge and Microwave Plasma Systems:**

Corona discharges occur in sharp-point electrode systems under high voltage, commonly used for surface modification of packaging films (Kumar et al., 2022). Microwave-induced plasma, on the other hand, uses electromagnetic radiation (2.45 GHz) to generate plasma under low pressure, yielding highly energetic species effective for microbial inactivation in liquids (Misra et al., 2021).

### 2.4 Process Parameters Affecting Plasma Efficacy:

The efficacy of cold plasma treatment depends on multiple operational parameters including voltage, frequency, treatment time, electrode distance, humidity, and feed gas composition (Thirumdas et al., 2020). Short treatment durations (typically <5 minutes) are sufficient for microbial inactivation, while extended exposure may induce oxidation or textural changes. Moisture enhances the formation of hydroxyl radicals, increasing bactericidal action (Tolouie et al., 2018). Likewise, combining plasma with mild heating or UV can yield synergistic effects, reduce microbial loads while maintain sensory integrity (Martillanes et al., 2022).

### 2.5 Safety and Physicochemical Considerations:

Although CP is non-thermal, its reactive nature necessitates careful optimization to prevent nutrient loss or undesirable oxidation. Studies have shown minimal effects on vitamins C and E, phenolics, and amino acids when plasma is operated under mild conditions (Misra et al., 2021). The risk of forming toxic residues is low, as RONS have short lifetimes and revert to stable molecules such as $O_2$ and $H_2O$ post-treatment (Dobrynin et al., 2021). Importantly, regulatory assessments have confirmed that plasma-treated foods do not exhibit chemical residues or harmful byproducts when properly processed (EFSA, 2021). Overall, understanding the plasma generation physics, chemistry, and system design is fundamental to optimizing its performance for food preservation. By precisely tuning these parameters, cold plasma technology can deliver efficient microbial safety while retaining food quality and minimizing environmental impact—positioning it as one of the most promising innovations in sustainable food processing (Liao et al., 2024).

## 3. Mechanisms of Microbial Inactivation and Enzyme Denaturation in Cold Plasma Systems:

The microbial inactivation mechanism of cold plasma (CP) is complex and multifactorial, involving physical, chemical, and biological interactions at the cellular and molecular levels. Unlike thermal processing, CP destroys microorganisms primarily through oxidative stress, UV radiation, charged particle bombardment, and electrostatic disruption, all occurring at near-ambient temperatures (Laroussi, 2018; Pankaj et al., 2021). The simultaneous presence of reactive oxygen and nitrogen species (RONS), short-lived radicals, and photons enables CP to attack multiple cellular targets—including the cell wall, plasma membrane, DNA, and intracellular proteins—resulting in irreversible loss of cellular integrity (Misra et al., 2019).

### 3.1 Oxidative Stress and Membrane Damage:

The cell membrane is the first line of defense against plasma-induced stress. Reactive oxygen species such as hydroxyl radicals (•OH), singlet oxygen ($^1O_2$), ozone ($O_3$), and hydrogen peroxide ($H_2O_2$) are generated when energetic electrons collide with atmospheric oxygen or water vapor (Tolouie et al., 2018). These radicals initiate lipid peroxidation, which disrupts the structural integrity of the microbial membrane, increases permeability, and causes leakage of cytoplasmic contents (Thirumdas et al., 2020). In *Escherichia coli* and *Listeria monocytogenes*, plasma exposure has been shown to cause morphological changes such as cell shrinkage, wall pitting, and cytoplasmic collapse under scanning electron microscopy (SEM) (Niemira, 2012; Kim et al., 2020). The oxidation of membrane phospholipids and proteins leads to loss of selective permeability and enzyme dysfunction, effectively halting respiration and nutrient transport (Danilova et al., 2022). RONS also oxidize thiol groups and disulfide bridges in membrane-bound proteins, impairing their structural stability (Misra et al., 2021).

### 3.2 DNA and Nucleic Acid Modifications:

Cold plasma generates both reactive species and ultraviolet photons (200–280 nm), which synergistically damage microbial DNA. UV photons induce thymine dimerization, a process where adjacent thymine bases in DNA become covalently bonded, preventing proper replication (Laroussi, 2018). Simultaneously, reactive nitrogen species such as nitric oxide (NO) and peroxynitrite ($ONOO^-$) cause nitrosative stress, leading to base deamination, strand breaks, and cross-linking of nucleic acids (Pankaj et al., 2021). Studies using electrophoretic and spectroscopic analyses have shown that plasma treatment can cause fragmentation of bacterial genomic DNA and reduce its amplification potential in polymerase chain reaction (PCR) assays (Thirumdas et al., 2020). Importantly, this DNA degradation occurs without significant heating, confirming that non-thermal plasma-induced chemical damage is the primary inactivation pathway (Bourke & Keener, 2022).

### 3.3 Protein Oxidation and Enzyme Denaturation:

In addition to DNA, microbial enzymes and structural proteins are major plasma targets. Reactive oxygen species oxidize amino acids such as cysteine, methionine, and tryptophan, leading to carbonyl formation and protein aggregation (Tolouie et al., 2018). Enzymes crucial for cellular metabolism—such as dehydrogenases, catalases, and ATPases—lose activity due to oxidation of active sites and conformational unfolding (Misra et al., 2021). Cold plasma also affects food-related enzymes, which are often responsible for undesirable quality changes such as browning or off-flavor formation. For example, plasma treatment effectively inactivates polyphenol oxidase (PPO) and peroxidase (POD) in fruits and vegetables, thereby preventing enzymatic browning (Surowsky et al., 2016). Similarly, lipoxygenase (LOX) and pectin methylesterase (PME) in juices and purees are denatured under mild plasma exposure, extending product shelf life while preserving sensory quality (Thirumdas et al., 2020). Enzyme inactivation follows a pseudo-first-order kinetic model, primarily governed by the concentration of reactive species and exposure duration (Bourke & Keener, 2022).

### 3.4 Cellular Respiration and Energy Disruption:

Beyond surface oxidation, plasma exposure leads to intracellular metabolic arrest. Reactive oxygen species cause depolarization of cell membranes, disrupting proton gradients and ATP synthesis (Laroussi, 2018). The accumulation of oxidized molecules interferes with the tricarboxylic acid (TCA) cycle and glycolysis, ultimately leading to apoptosis-like cell death (Niemira, 2012). In Gram-negative bacteria, damage to the outer membrane and periplasmic space enhances susceptibility to secondary oxidative attacks (Danilova et al., 2022). Gram-positive bacteria, although more resistant due to thicker peptidoglycan layers, eventually succumb to oxidative degradation with longer treatment durations (Pankaj et al., 2021).

**3.5 Biofilm Disruption and Spore Inactivation:**

Microbial biofilms—structured communities encased in extracellular polymeric substances (EPS)—are notoriously resistant to conventional sanitization. Cold plasma provides a highly effective means for biofilm disruption through oxidative cleavage of polysaccharides and extracellular proteins (Misra et al., 2019). Plasma-generated RONS degrade EPS and increase the permeability of biofilms, enabling deep penetration of reactive agents (Bhatia et al., 2021). For bacterial spores, which are among the most resistant forms of life, plasma induces inactivation through physical etching of spore coats, oxidation of dipicolinic acid, and damage to inner membranes (Laroussi, 2018). Studies have demonstrated a >4-log reduction in *Bacillus subtilis* spores using dielectric barrier discharge (DBD) systems within minutes of exposure (Tolouie et al., 2018). Plasma jets and gliding arc discharges have also proven effective in reducing fungal spores and mycotoxin-producing molds on cereals and nuts (Bourke & Keener, 2022).

**3.6 Synergistic Mechanisms with Other Non-Thermal Technologies:**

Recent investigations have revealed that combining cold plasma with other non-thermal processes—such as pulsed electric fields (PEF), ultraviolet-C irradiation, or ultrasound—can significantly enhance microbial inactivation efficiency while minimizing oxidative side effects (Martillanes et al., 2022). Plasma–ultrasound hybridization enhances mass transfer of reactive species, while plasma–PEF integration accelerates cell membrane permeabilization (Liao et al., 2024). Such multi-hurdle approaches are increasingly viewed as the future of clean-label, energy-efficient food preservation, achieving microbial safety without compromising quality.

**3.7 Implications for Food Quality and Safety:**

A critical advantage of cold plasma lies in its ability to achieve microbial safety without excessive heating or chemical additives. Properly optimized plasma treatment maintains food color, texture, and nutrients while ensuring pathogen reduction to safe levels (Misra et al., 2021). Moreover, since plasma-generated RONS revert rapidly to stable molecules like $O_2$, $H_2O$, and $H_2O_2$, there are minimal residual effects, aligning with consumer expectations for natural and minimally processed foods (Dobrynin et al., 2021; EFSA, 2021). The broad-spectrum antimicrobial efficacy of cold plasma—combined with its environmental sustainability and operational flexibility—positions it as a transformative tool in next-generation food preservation systems. However, understanding the mechanistic details of microbial and enzymatic inactivation remains essential for tailoring plasma parameters to specific food matrices and ensuring consistent industrial-scale performance (Bourke & Keener, 2022).

**4. Effects of Cold Plasma on Nutritional, Sensory, and Functional Properties of Foods:**

The success of any food preservation technology depends not only on its ability to ensure microbial safety but also on its capacity to preserve or enhance nutritional and sensory qualities. Cold plasma (CP), as a non-thermal technology, offers a major advantage in maintaining the fresh-like characteristics of foods because it operates at low temperatures and requires no chemical preservatives (Misra et al., 2019; Pankaj et al., 2021). However, plasma-induced reactive species (RONS) can potentially alter sensitive biomolecules such as vitamins, pigments, lipids, and proteins, influencing both nutritional composition and sensory perception (Thirumdas et al., 2020; Danilova et al., 2022). Understanding these effects is critical for optimizing plasma parameters to achieve microbial safety without compromising food quality.

### 4.1 Impact on Nutritional Components:

**Vitamins:**

Vitamins, particularly water-soluble ones like vitamin C and B-complex, are susceptible to oxidation. Studies have reported that plasma exposure for short durations (≤3 minutes) results in minimal ascorbic acid degradation (<10%) in fruit juices and fresh produce (Misra et al., 2021). Prolonged or high-voltage treatments may, however, increase oxidation losses due to hydroxyl radical activity (Tolouie et al., 2018). For example, Kim et al. (2020) demonstrated that cold plasma treatment of strawberries for 90 seconds retained over 92% of vitamin C, while Thirumdas et al. (2020) found similar stability in plasma-treated tomato juice. Fat-soluble vitamins (A, D, E, and K) are comparatively stable because they are embedded in lipid phases, offering protection from short-lived reactive oxygen species (Danilova et al., 2022).

**Minerals:**

Plasma exposure generally does not affect mineral content since metals are not easily oxidized under the short treatment times and moderate discharge energies used in food processing (Bourke & Keener, 2022). Trace elements such as calcium, magnesium, and potassium remain stable, as confirmed in milk and fruit matrices treated with dielectric barrier discharge (DBD) plasma (Misra et al., 2021).

**Antioxidants and Phytochemicals:**

Cold plasma may induce mild oxidation of phenolic compounds, yet some studies report enhanced total phenolic content (TPC) due to the breakdown of complex polyphenols and improved extractability (Thirumdas et al., 2020). For instance, Pankaj et al. (2021) observed a 12% increase in TPC in apple juice after plasma exposure, attributed to depolymerization of bound phenolic structures. Similarly, Tolouie et al. (2018) noted an increase in antioxidant activity in plasma-treated pomegranate juice, linked to plasma-stimulated enzyme release from cell walls. These findings suggest that controlled plasma exposure can promote bioavailability of functional compounds while maintaining redox balance.

### 4.2 Effects on Pigments and Color Attributes:

Color plays a vital role in consumer perception and acceptance of foods. Plasma-induced oxidative reactions can affect natural pigments such as anthocyanins, chlorophylls, and carotenoids, either through oxidation or structural modification (Misra et al., 2019). In fruits and vegetables, color retention is largely dependent on treatment intensity. Kim et al. (2020) demonstrated that cold plasma exposure of spinach leaves for less than 120 seconds retained over 95% of chlorophyll content, while extended treatment (beyond 5 minutes) resulted in slight yellowing due to chlorophyll oxidation. For carotenoid-rich foods like carrots and tomatoes, short-duration plasma treatment improved color uniformity and reduced enzymatic browning by inactivating polyphenol oxidase (PPO) (Thirumdas et al., 2020). Plasma-treated meat products exhibit distinct color stability outcomes. Danilova et al. (2022) found that reactive nitrogen species (NO) produced during plasma exposure contributed to myoglobin nitrosylation, imparting a pink hue similar to that achieved with nitrite curing—suggesting potential for nitrite reduction in cured meats. This finding is highly relevant for clean-label processing, where reducing chemical additives is a priority (Bourke & Keener, 2022).

### 4.3 Lipid Oxidation and Flavor Compounds:

One of the key quality concerns during plasma treatment is lipid oxidation, particularly in high-fat foods. Plasma-generated ozone and hydroxyl radicals can attack unsaturated fatty acids, producing secondary oxidation products like aldehydes and ketones (Tolouie et al., 2018). However, lipid oxidation remains minimal when plasma is applied under low voltage and short duration or when inert gases such as argon or nitrogen are used as the plasma medium (Pankaj et al., 2021). For instance, Misra et al. (2021) reported negligible peroxide value increases (<0.2 meq/kg) in plasma-treated chicken fillets exposed to argon-based plasma for 120 seconds. Likewise, Danilova et al. (2022) found that argon–oxygen plasma caused less oxidation than air plasma in beef due to reduced ozone formation. Sensory panel evaluations generally indicate no off-flavors or rancidity when plasma exposure is controlled (Niemira, 2012). Interestingly, plasma treatment may enhance desirable aroma compounds in certain plant foods. Thirumdas et al. (2020) observed that short plasma exposure increased volatile ester and aldehyde formation in mango pulp, enhancing fruity aroma, likely due to enzymatic activation. Thus, with proper optimization, plasma can modulate flavor profiles favorably without undesirable oxidative byproducts.

### 4.4 Influence on Texture and Structural Integrity:

The structural integrity of food components—especially in fresh produce and protein-based products—is influenced by the interplay between plasma's physical and chemical effects. The non-thermal nature of cold plasma ensures minimal impact on the bulk temperature, preserving cell wall turgor and moisture content (Misra et al., 2019). Studies on lettuce, apples, and strawberries treated with DBD plasma showed no significant change in hardness or texture parameters after treatments under 3 minutes (Kim et al., 2020; Thirumdas et al., 2020). In protein-based foods, plasma exposure induces surface modifications that may improve emulsification, foaming, and solubility characteristics (Bhatia et al., 2021). The partial unfolding of proteins increases the accessibility of hydrophilic and hydrophobic sites, enhancing their functional properties. However, excessive plasma exposure can lead to cross-linking and denaturation, which negatively affects tenderness and water-holding capacity (Danilova et al., 2022). Thus, balancing plasma intensity is essential to achieve structural benefits without quality deterioration.

### 4.5 Overall Quality Retention and Consumer Acceptance:

The overarching advantage of cold plasma lies in its ability to preserve sensory and nutritional quality while ensuring microbial safety. Multiple studies report that CP-treated foods maintain natural color, aroma, and texture, with sensory panels rating them comparable to untreated or fresh controls (Misra et al., 2021; Bourke & Keener, 2022). Furthermore, consumer perception of plasma technology is largely positive when framed as an "eco-friendly, chemical-free" preservation method (Liao et al., 2024). The balance between microbial inactivation and quality retention depends on optimizing discharge parameters, feed gas composition, and exposure time. The integration of computational models and artificial intelligence (AI)-based control systems is expected to enhance this optimization, minimizing quality losses while ensuring process repeatability (Xia et al., 2023). In conclusion, cold plasma—when appropriately designed and operated—can maintain or even improve the nutritional, functional, and sensory profile of foods, offering a sustainable route to high-quality, safe, and clean-label food products.

**5. Plasma-Activated Liquids (PALs) and Their Role in Food Preservation and Disinfection:**

The concept of plasma-activated liquids (PALs)—including plasma-activated water (PAW) and plasma-treated solutions—has emerged as a transformative approach in non-thermal food preservation. PALs are generated when cold plasma interacts with liquids such as water, buffer solutions, or electrolytes, leading to the dissolution of reactive oxygen and nitrogen species (RONS), including hydrogen peroxide ($H_2O_2$), nitrate ($NO_3^-$), nitrite ($NO_2^-$), ozone ($O_3$), hydroxyl radicals (•OH), and peroxynitrite ($ONOO^-$) (Thirumdas et al., 2018; Bourke & Keener, 2022). These species confer potent antimicrobial and antioxidant properties, allowing PALs to be used as indirect plasma treatments for microbial decontamination, enzyme inactivation, and residue removal in food and packaging systems.

**5.1 Generation and Physicochemical Characteristics of PALs:**

The generation of PALs depends on the plasma discharge type, feed gas composition, and treatment time. Common plasma systems include dielectric barrier discharge (DBD), gliding arc discharge, and plasma jets, using gases such as air, oxygen, nitrogen, or argon (Misra et al., 2019). When plasma interacts with water, it triggers a cascade of electrochemical reactions that alter its physicochemical properties—pH decreases (typically from 7.0 to 3.0–4.0), oxidation–reduction potential (ORP) increases (>500 mV), and electrical conductivity rises due to ionization (Pankaj et al., 2021). Liao et al. (2024) noted that PAW generated under air DBD plasma contained stable concentrations of nitrate and hydrogen peroxide for over 20 hours, indicating potential for storage and transportation. Furthermore, Thirumdas et al. (2018) reported that RONS concentration and half-life can be fine-tuned by adjusting the plasma exposure duration, discharge voltage, and gas type—oxygen-based plasmas produce higher oxidative strength, while nitrogen-based plasmas generate longer-lived reactive species. These chemical dynamics determine the antimicrobial potency and oxidative selectivity of PALs in food applications.

**5.2 Antimicrobial Mechanisms of PALs:**

The antimicrobial activity of plasma-activated liquids stems from their oxidative stress mechanisms on microbial cells. RONS in PALs cause lipid peroxidation, DNA fragmentation, and protein oxidation, ultimately leading to cell death (Misra et al., 2019). Smet et al. (2021) demonstrated that PAW treatment of Listeria monocytogenes and Salmonella enterica resulted in complete inactivation (>6 log CFU/mL) within 5 minutes. Bourke & Keener (2022) further confirmed similar efficacy against fungal spores, yeasts, and viruses in fruit juice and dairy matrices. The antimicrobial efficiency depends on solution chemistry—for instance, acidic PAW enhances hydroxyl radical formation, whereas neutral or alkaline PAW favors nitrite-mediated disinfection pathways (Danilova et al., 2022). Reactive nitrogen species play a synergistic role by nitrosating cellular thiols and disrupting membrane integrity. These findings suggest that PALs exhibit both oxidative and nitrosative stress responses, providing broad-spectrum antimicrobial activity without generating harmful residues or off-flavors.

**5.3 Applications in Food Washing and Surface Decontamination:**
PALs have found wide applications in surface decontamination of fresh produce, seafood, and meat products, replacing traditional chlorine-based sanitizers. For example, Thirumdas et al. (2018) demonstrated that PAW washing of fresh lettuce reduced E. coli and Salmonella by >4 log CFU without altering color or texture. Kim et al. (2020) reported similar efficacy in strawberry washing, with microbial reductions comparable to sodium hypochlorite but without residual chlorine compounds. In seafood processing, Bhatia et al. (2021) observed that PAW immersion of shrimp and fish fillets effectively reduced total viable counts while maintaining freshness indicators such as pH, TVB-N, and sensory attributes. The treatment also prevented biofilm formation on stainless-steel and polyethylene conveyor surfaces, a major challenge in processing plants (Pankaj et al., 2021). These studies highlight PAW as a sustainable and safe decontamination method suitable for organic and clean-label processing environments.

**5.4 Role in Enzyme Inactivation and Quality Preservation:**
Enzyme inactivation is critical in preventing undesirable changes in color, texture, and flavor during storage. PALs have shown promising effects on oxidative enzymes such as polyphenol oxidase (PPO), peroxidase (POD), and lipoxygenase (LOX). Misra et al. (2021) found that PAW treatment of apple juice reduced PPO activity by 80% within 3 minutes, thereby inhibiting enzymatic browning. Similarly, Danilova et al. (2022) observed suppression of LOX activity in soybean extract treated with nitrogen-based PAW, which minimized lipid oxidation during refrigerated storage. Importantly, PALs can achieve enzyme inactivation without significant thermal input, ensuring retention of vitamins, pigments, and antioxidants. Thirumdas et al. (2020) reported that PAW-treated tomato juice maintained >90% of its total phenolic content and vitamin C levels. These results demonstrate that PALs combine microbial safety and nutritional preservation, offering an eco-friendly alternative to chemical or heat-based treatments.

**5.5 Integration of PALs with Existing Preservation Systems:**
The adaptability of plasma-activated liquids allows their integration with other non-thermal or mild preservation techniques, enhancing overall effectiveness. When combined with ultrasound, UV-C irradiation, or mild heat, PAW shows synergistic antimicrobial and enzymatic inactivation effects (Bourke & Keener, 2022). For example, *Liao et al. (2024)* reported that PAW combined with mild heat (50°C for 2 minutes) achieved 7-log reductions of *Listeria* in milk, outperforming individual treatments. In packaging systems, PAW can be incorporated into active coatings or spray systems, providing continuous antimicrobial protection. Emerging studies explore electrostatic spraying of PALs on packaging films and

containers to form RONS-rich surfaces that inhibit microbial growth during storage (Pankaj et al., 2021). Furthermore, in-package plasma activation—where liquids sealed with food are exposed to plasma discharge—represents a novel technique for maintaining sterility in ready-to-eat products while minimizing oxidation (Bhatia et al., 2021).

### 5.6 Future Perspectives of PALs in Sustainable Food Systems:

The growing interest in PALs aligns with the global push for chemical-free, energy-efficient, and waste-minimizing food preservation. However, standardization challenges remain concerning RONS quantification, treatment reproducibility, and regulatory acceptance. The long-term stability and safety of reactive species in treated foods also require comprehensive toxicological assessment (Bourke & Keener, 2022). Advanced analytical tools—such as electron paramagnetic resonance (EPR) spectroscopy, high-resolution mass spectrometry, and computational plasma modeling—are being employed to elucidate the complex interactions between RONS and food components. Coupled with AI-driven process optimization and sensors for real-time plasma diagnostics, these innovations are expected to refine PAL design for industrial scalability and global acceptance (Liao et al., 2024). Ultimately, plasma-activated liquids represent a cornerstone of next-generation food preservation, bridging the gap between high safety standards and green processing principles.

## 6. Industrial Applications and Scale-Up Challenges of Cold Plasma Technology:

Cold plasma (CP) technology has evolved from a laboratory innovation into a promising candidate for industrial-scale food processing and preservation. Its non-thermal, eco-efficient characteristics offer immense potential for applications such as surface decontamination, equipment sterilization, packaging treatment, enzyme control, and shelf-life extension (Misra et al., 2019; Bourke & Keener, 2022). However, transitioning from lab-scale to full-scale implementation poses significant challenges in terms of reactor design, energy efficiency, process uniformity, and regulatory compliance. Understanding these aspects is essential for developing sustainable and commercially viable plasma-based food systems.

### 6.1 Industrial-Scale Reactor Configurations

Industrial applications of cold plasma rely on diverse reactor configurations tailored to specific product characteristics and throughput requirements. The most common designs include:

- Dielectric Barrier Discharge (DBD) Systems: DBD reactors are preferred for surface treatment of solid foods and packaging films. Their modular design allows integration into conveyor systems for continuous processing (Pankaj et al., 2021).
- Gliding Arc and Corona Discharges: These systems generate plasma at atmospheric pressure, suitable for large-area treatments such as grain or nut decontamination (Thirumdas et al., 2018).
- Plasma Jets: Useful for irregular surfaces and delicate products such as fruits and bakery items. Kim et al. (2020) demonstrated effective decontamination of strawberries using argon-based plasma jets with minimal quality loss.
- In-Package Plasma Systems: This innovative approach generates plasma directly within sealed packages, ensuring post-packaging sterilization and extending product shelf life. Danilova et al. (2022) reported a 3-log reduction in microbial counts in ready-to-eat salads using in-package plasma without compromising sensory quality.

Industrial systems are now being developed with automated control of discharge voltage, gas flow rate, and treatment time, ensuring process reproducibility and scalability (Bourke & Keener, 2022). Integration with robotic handling and real-time sensors allows CP systems to adapt to varying product geometries, improving uniformity of exposure.

**6.2 Food Sector Applications:**

**Fresh Produce and Juices:**

Cold plasma has achieved commercial viability in fruit and vegetable processing, particularly for reducing surface pathogens and pesticide residues. Thirumdas et al. (2020) showed that DBD plasma treatment reduced E. coli and Salmonella in lettuce and spinach by >4 log CFU with negligible color changes. Additionally, Liao et al. (2024) reported that plasma-assisted washing lines reduced microbial load in mango and apple juice industries, achieving pathogen control without chemical sanitizers.

**Meat, Poultry, and Seafood:**

In animal-based foods, CP effectively inactivates Listeria monocytogenes, Staphylococcus aureus, and Salmonella spp. on meat surfaces. Bhatia et al. (2021) demonstrated that air plasma treatment on chicken fillets achieved a 99.9% microbial reduction, while maintaining color and tenderness. CP is also applied in seafood industries to reduce vibrio and spoilage bacteria, thereby extending refrigerated shelf life by up to 50% (Misra et al., 2021).

**Grains, Spices, and Dairy:**

Plasma treatment of grains and spices offers chemical-free decontamination of spores and aflatoxins (Danilova et al., 2022). Bourke & Keener (2022) found that plasma exposure significantly reduced fungal contamination in wheat and maize, while retaining germination potential. In dairy processing, plasma-activated water (PAW) has been applied for cleaning-in-place (CIP) systems, replacing caustic chemicals with minimal energy input.

**Food Packaging and Equipment Sterilization:**

Cold plasma is now used for surface activation and sterilization of packaging materials such as polyethylene, polypropylene, and biopolymer films (Misra et al., 2019). Plasma treatment enhances surface energy, improving adhesion for coatings or printing while imparting antimicrobial functionality. In addition, in-line plasma sterilization units for conveyor belts and packaging lines reduce microbial cross-contamination, a critical feature in ready-to-eat food production (Liao et al., 2024).

**6.3 Energy Efficiency and Environmental Benefits:**

Cold plasma's energy efficiency is one of its most attractive features. Compared to conventional pasteurization, CP consumes less energy per unit mass of treated food since it avoids bulk heating (Pankaj et al., 2021). The technology operates at atmospheric pressure and room temperature, eliminating the need for vacuum or refrigeration systems during treatment. Moreover, since plasma gases (such as air, nitrogen, or argon) are non-toxic and recyclable, the process generates minimal chemical waste and carbon emissions (Bourke & Keener, 2022). Thirumdas et al. (2018) calculated that cold plasma processing of 1 ton of leafy vegetables consumed nearly 60% less energy compared to chlorine-based washing systems. Additionally, CP systems can be powered by renewable energy sources, aligning with the principles of green food engineering and sustainable manufacturing.

**6.4 Scale-Up and Process Uniformity Challenges:**

Despite promising outcomes, scaling cold plasma technology from laboratory prototypes to industrial throughput remains challenging. One of the main limitations is non-uniform plasma exposure due to complex food geometries and shadowing effects. Irregular surfaces—such as leafy vegetables or meat cuts—may receive uneven doses, leading to variable microbial inactivation (Misra et al., 2021). To overcome this, research focuses on rotating electrodes, multi-nozzle plasma arrays, and conveyor-based reactors that distribute plasma uniformly (Bhatia et al., 2021). Advanced computational models are also being developed to simulate plasma–food interactions, predicting electric field distributions and optimizing gas composition for uniform treatment (Xia et al., 2023). Another challenge is processing validation and standardization. Unlike thermal pasteurization, plasma treatment lacks universal reference parameters such as time–temperature equivalence. As a result, regulatory agencies require detailed documentation of process repeatability, safety validation, and chemical residue analysis (Liao et al., 2024).

**6.5 Regulatory, Safety, and Consumer Acceptance:**

For successful commercialization, regulatory compliance and consumer confidence are essential. Regulatory bodies such as the U.S. Food and Drug Administration (FDA) and European Food Safety Authority (EFSA) currently recognize plasma-treated water and surfaces as safe under specific conditions, but approvals for direct plasma treatment of food products are still under evaluation (Bourke & Keener, 2022).

Public perception of plasma technology largely depends on communication and transparency. Surveys conducted by Liao et al. (2024) indicate that consumers associate plasma-treated foods with “chemical-free” and “eco-friendly” processing when informed of its natural basis in atmospheric gases. Furthermore, life-cycle assessments (LCAs) confirm that plasma systems have lower environmental footprints compared to chemical sanitization and thermal pasteurization, reinforcing their sustainability credentials.

**6.6 Toward Industry 4.0 Integration:**

Future industrial plasma systems are expected to integrate digital twins, artificial intelligence (AI), and IoT-based monitoring for precision process control (Xia et al., 2023). Machine-learning algorithms can predict optimal discharge parameters based on real-time plasma diagnostics, ensuring consistent microbial reduction with minimal energy consumption. Coupled with sensor-driven feedback systems and blockchain-enabled traceability, such integrations will revolutionize smart, traceable, and data-driven food preservation systems.

**7. Integration of Cold Plasma with Other Emerging Non-Thermal Technologies: Synergistic Preservation Strategies:**

While cold plasma (CP) has established itself as a powerful standalone non-thermal technology, its integration with other advanced preservation methods is increasingly recognized as a key strategy to enhance microbial inactivation efficiency, energy optimization, and product quality retention. Hybrid systems—combining CP with ultrasound, pulsed electric fields (PEF), ultraviolet (UV) irradiation, ozone, or mild thermal treatments—capitalize on the complementary mechanisms of these technologies to achieve multi-hurdle preservation (Misra et al., 2019; Bourke & Keener, 2022). Such synergistic approaches align with the “hurdle technology” principle, where multiple mild treatments collectively ensure food safety without significantly altering sensory or nutritional properties (Pankaj et al., 2021).

**7.1 Rationale for Combined Non-Thermal Approaches:**

Each non-thermal technology operates through distinct mechanisms: CP generates reactive oxygen and nitrogen species (RONS) and UV photons; ultrasound produces cavitational shear and localized heating; PEF induces electroporation of microbial membranes; and ozone contributes oxidative disinfection (Thirumdas et al., 2020). When combined strategically, these treatments enhance microbial inactivation kinetics, lower energy consumption, and minimize process time while maintaining desirable food quality (Bhatia et al., 2021).

For instance, plasma-induced stress can increase cell membrane permeability, allowing ultrasound or mild heat to penetrate and further disrupt microbial cells (Liao et al., 2024). Conversely, pre-treatment with ultrasound or PEF may enhance plasma efficacy by dispersing biofilms or increasing surface roughness, facilitating more effective plasma–microbe interactions (Misra et al., 2021).

**7.2 Cold Plasma–Ultrasound (CP–US) Combination:**

The combination of CP and ultrasound leverages the mechanical cavitation from ultrasound with the chemical oxidation from plasma-generated species. Thirumdas et al. (2018) demonstrated that CP–US treatment of orange juice achieved a 6-log reduction of E. coli and Saccharomyces cerevisiae while preserving over 90% of vitamin C and phenolic compounds. The cavitation effect enhanced RONS penetration and reduced plasma exposure time by nearly 40%. In another study, Bhatia et al. (2021) showed that CP–US treatment of milk resulted in higher microbial reductions and reduced lipase activity compared to either method alone, indicating synergy between mechanical disruption and oxidative stress. Additionally, ultrasound promotes better mass transfer of reactive species and improves uniformity of plasma action, particularly in liquid and semi-solid foods.

**7.3 Cold Plasma–Pulsed Electric Field (CP–PEF) Combination:**

PEF is widely used for cell membrane electroporation and enzyme inactivation, making it an ideal complement to plasma-based oxidation. The CP–PEF combination enhances microbial lethality by first inducing reversible electroporation, followed by irreversible oxidative damage.

Misra et al. (2019) reported that combining CP and PEF treatments achieved >7 log CFU/mL reduction in Listeria monocytogenes in carrot juice while preserving β-carotene and total phenolic content. Bourke & Keener (2022) further confirmed that PEF pre-treatment facilitates deeper plasma penetration into cell clusters, enhancing inactivation of resistant spores and biofilms. The synergistic action also reduces total energy consumption by 25–30% compared to standalone processes.

**7.4 Cold Plasma–Ultraviolet (CP–UV) Combination:**

The plasma–UV hybrid approach exploits the synergistic effects of UV photons (for nucleic acid disruption) and plasma-generated radicals (for oxidative membrane damage). Danilova et al. (2022) demonstrated that CP–UV treatment of fresh strawberries achieved >5 log reduction in Botrytis cinerea spores, outperforming individual UV or plasma treatments. This combination is particularly effective for surface sterilization of transparent packaging and fresh-cut produce. The UV radiation enhances RONS activation in plasma-treated air, while plasma prevents microbial recovery by damaging DNA repair enzymes. The approach is also energy-efficient since UV enhances plasma-induced photolysis reactions, allowing lower discharge voltages (Pankaj et al., 2021).

**7.5 Cold Plasma–Ozone (CP–$O_3$) Combination:**

Ozone, a strong oxidizing agent, has long been used as a disinfectant in food processing. When combined with cold plasma, ozone generation can be in-situ enhanced, intensifying antimicrobial efficacy (Liao et al., 2024). Thirumdas et al. (2020) reported that CP–$O_3$ treatment of spinach leaves reduced microbial load by 6 logs with minimal chlorophyll degradation. Similarly, Misra et al. (2021) found that CP–$O_3$ treatment in meat processing lines achieved superior biofilm removal compared to ozone alone. The key advantage of this integration lies in the self-sustained generation of reactive species, as plasma discharge naturally produces ozone, hydroxyl radicals, and peroxides. The process also eliminates the need for additional chemical oxidants, supporting eco-friendly, residue-free preservation.

**7.6 Cold Plasma–Mild Thermal or MAP Systems:**

Combining cold plasma with mild thermal treatments (temperatures ≤50°C) or modified atmosphere packaging (MAP) offers dual benefits of microbial inactivation and shelf-life enhancement. Kim et al. (2020) found that CP combined with mild heat treatment improved microbial inactivation of Listeria monocytogenes in milk by twofold compared to plasma alone. The mild heat enhanced membrane fluidity, facilitating deeper penetration of RONS. When applied in combination with MAP, plasma can maintain low-oxygen conditions inside packages, reducing oxidation while sterilizing headspace gases (Danilova et al., 2022). The in-package plasma + MAP hybrid is now being tested for ready-to-eat foods and minimally processed salads, achieving extended microbial safety without compromising sensory attributes.

**7.7 Process Optimization and Synergistic Modelling:**

Hybrid plasma systems require optimization of multiple parameters such as exposure time, discharge voltage, frequency, gas composition, and pre/post-treatment conditions. To address this complexity, response surface methodology (RSM) and machine learning models are increasingly used to predict optimal combinations for maximum inactivation and quality retention (Xia et al., 2023). For instance, Liao et al. (2024) used AI-assisted predictive modeling to optimize CP–PEF combinations in fruit juice, achieving 98% energy savings and improved vitamin retention. Similarly, Bhatia et al. (2021) employed computational fluid dynamics (CFD) to simulate reactive species distribution in CP–US systems, enhancing process uniformity.

**7.8 Benefits, Limitations, and Future Prospects:**

Hybridization of CP with other non-thermal technologies provides several advantages: enhanced microbial control, reduced treatment time, improved energy efficiency, and better retention of sensory and nutritional attributes (Misra et al., 2019). However, limitations persist, including equipment complexity, synchronization of treatment parameters, and capital costs. The future of plasma hybrid systems lies in compact, modular, and AI-integrated designs that can adaptively adjust parameters for different product categories. Combining CP with green energy sources (e.g., solar-powered plasma systems) and integrating real-time sensors for RONS monitoring will further enhance sustainability and regulatory compliance.

Ultimately, synergistic plasma systems embody the next frontier in non-thermal, intelligent, and sustainable food preservation, bridging microbial safety with clean-label processing.

**8. Cold Plasma-Enabled Packaging Innovations and Smart Preservation Systems:**

Recent advances in cold plasma (CP) technology have extended beyond direct food treatment into packaging material modification and smart preservation systems. Plasma-assisted surface engineering enables the creation of active, antimicrobial, and intelligent packaging that enhances food safety, prolongs shelf life, and minimizes environmental impact. The ability of plasma to modify polymer surfaces at low temperatures without altering their bulk properties has positioned it as a sustainable tool for developing the next generation of food packaging materials (Butscher et al., 2016; Misra et al., 2021).

**8.1 Plasma Surface Modification of Packaging Materials:**

Cold plasma can functionalize polymer surfaces (such as polyethylene, polypropylene, and polylactic acid) by introducing oxygen- or nitrogen-containing groups like hydroxyl, carboxyl, or amine functionalities. These changes improve surface energy, adhesion, hydrophilicity, and printability (Yildirim et al., 2022). According to Pankaj et al. (2014), dielectric barrier discharge (DBD) plasma treatment enhanced the oxygen permeability of PLA films by 38%, making them more suitable for modified atmosphere packaging (MAP). Similarly, Bourke & Keener (2022) reported that air plasma improved surface wettability of PET films, enhancing their ability to bond with biodegradable coatings such as chitosan and zein.

Plasma treatment also facilitates coating adhesion for nanocomposites or biopolymers that impart additional barrier or antimicrobial functionalities (Sharma et al., 2023). For instance, coating plasma-treated PET with ZnO nanoparticles or essential oil-loaded biopolymers significantly increased resistance against spoilage microorganisms and reduced oxygen transmission rates.

**8.2 Plasma-Activated Antimicrobial Packaging:**

Cold plasma can directly generate antimicrobial agents—such as reactive oxygen and nitrogen species (RONS), ozone, and UV photons—within or on the packaging surface. Thirumdas et al. (2020) demonstrated that plasma-treated polyethylene films exhibited strong antibacterial activity against E. coli and Listeria monocytogenes, maintaining efficacy for up to 15 days in cold storage. Moreover, plasma-activated water (PAW) can be used to impregnate biopolymer films with reactive species, creating sustained-release antimicrobial packaging. Xia et al. (2023) reported that starch-based films treated with PAW retained high bactericidal potential for 10 days, effectively extending the shelf life of fresh strawberries. This approach is eco-friendly since it eliminates the use of chemical preservatives while maintaining biodegradability.

Additionally, in-package plasma treatment allows sterilization of sealed products and headspace gases simultaneously (Misra et al., 2019). This eliminates post-packaging contamination risks, making it ideal for minimally processed fruits, meats, and ready-to-eat meals. Danilova et al. (2022) found that in-package CP treatment extended the shelf life of fresh-cut apples by 12 days, primarily due to the continuous release of reactive species that inhibited surface microbial growth.

**8.3 Plasma-Polymerized Coatings and Functional Films:**

Plasma polymerization enables the deposition of ultra-thin films with tailored barrier or antimicrobial properties on diverse substrates. Yildirim et al. (2022) reported that plasma-polymerized hexamethyldisiloxane (PP-HMDSO) coatings on PET improved oxygen barrier performance by 80% without compromising transparency or flexibility. Similarly, Misra et al. (2021) demonstrated that plasma-deposited titanium oxide films exhibited photocatalytic and antimicrobial behavior under visible light, suitable for high-moisture foods like seafood and poultry.

Plasma polymerization can also incorporate bioactive compounds, such as essential oils, silver ions, or natural antioxidants, to form active coatings with controlled release profiles (Sharma et al., 2023). These plasma-based coatings align with clean-label packaging trends, eliminating the need for synthetic preservatives while maintaining safety and freshness.

**8.4 Intelligent and Smart Plasma-Based Packaging Systems:**

The emergence of smart packaging technologies integrated with plasma treatment opens opportunities for real-time food freshness monitoring. Plasma-modified sensors and indicator films can detect gases (e.g., $CO_2$, $NH_3$) or volatile compounds emitted during spoilage. Bhatia et al. (2021) developed a plasma-treated anthocyanin-based indicator film that changed color from purple to green upon exposure to amines released from spoiled meat. Similarly, Liao et al. (2024) reported plasma-activated nanocellulose films embedded with pH-sensitive dyes, capable of detecting spoilage in dairy products with >95% accuracy. These intelligent systems provide a visual freshness indicator to consumers, promoting transparency and reducing food waste.

Plasma-enabled gas sensors and biosensors also offer advanced functionalities for digital food monitoring. Xia et al. (2023) demonstrated that plasma-engineered graphene oxide sensors could detect trace ethylene emissions, predicting fruit ripening and spoilage stages. Integration of these systems with Internet of Things (IoT) platforms can lead to “smart connected packaging” that continuously tracks and transmits quality data across the supply chain.

**8.5 Environmental Sustainability and Biodegradable Plasma-Treated Packaging:**

Cold plasma plays a significant role in enhancing the mechanical and barrier properties of biodegradable packaging materials such as starch, PLA, and cellulose-based films. Sharma et al. (2023) demonstrated that argon plasma treatment improved tensile strength and reduced water vapor permeability of starch films by cross-linking surface hydroxyl groups. This provides a sustainable alternative to synthetic polymers without compromising shelf life or mechanical stability.

Moreover, plasma-assisted grafting of natural polymers (like chitosan or alginate) onto bioplastics improves compostability and moisture resistance, reducing plastic pollution. Bourke & Keener (2022) emphasized that the low energy demand and chemical-free operation of plasma treatments make them compatible with circular economy goals and global sustainability frameworks such as the European Green Deal.

**8.6 Regulatory and Safety Considerations:**

Despite significant progress, regulatory acceptance of plasma-treated packaging remains under evaluation. Agencies such as the U.S. Food and Drug Administration (FDA) and European Food Safety Authority (EFSA) are assessing the migration of plasma-generated reactive species into foods. Misra et al. (2021) and Thirumdas et al. (2020) highlighted that appropriate process validation, toxicity studies, and residue monitoring are essential to ensure consumer safety. Encouragingly, most studies report no significant chemical migration or off-flavors when optimized plasma parameters are used.

**8.7 Future Directions:**

The future of plasma-enabled packaging lies in hybrid systems combining CP with biodegradable materials, natural antimicrobial agents, and digital sensing technologies. Development of energy-efficient plasma reactors, real-time monitoring tools for RONS, and life cycle assessment (LCA)-based evaluations will accelerate industrial translation (Xia et al., 2023).

The convergence of plasma technology with AI-driven design, additive manufacturing, and nanotechnology is expected to yield customizable, multi-functional packaging systems that enhance food safety, sustainability, and consumer engagement.

**9. Mechanisms of Microbial and Enzymatic Inactivation by Cold Plasma: Molecular and Biochemical Insights:**

Understanding the fundamental mechanisms underlying microbial and enzymatic inactivation by cold plasma (CP) is crucial for optimizing its application in food processing and preservation. The efficacy of CP depends on the synergistic action of reactive oxygen species (ROS), reactive nitrogen species (RNS), UV photons, charged particles, and electric fields, all of which collectively target microbial cell structures, enzymes, and nucleic acids (Misra et al., 2019; Bourke & Keener, 2022). The ability of plasma to achieve microbial decontamination without significant heat input has revolutionized non-thermal food preservation technologies (Thirumdas et al., 2020).

**9.1 Reactive Species Generation and Interactions:**

Cold plasma discharges—typically generated through dielectric barrier discharge (DBD), plasma jets, or corona systems—produce a cocktail of short- and long-lived reactive species, including hydroxyl radicals (•OH), ozone ($O_3$), atomic oxygen (O), hydrogen peroxide ($H_2O_2$), nitric oxide (NO), and nitrogen dioxide ($NO_2$). These species interact with microbial cells and food matrices through oxidation, nitration, and radical recombination reactions (Pankaj et al., 2021). According to Yildirim et al. (2022), the dominant mechanism in atmospheric-pressure plasma involves the reaction of •OH and $O_3$ with unsaturated fatty acids and amino acids, leading to oxidative stress and membrane damage. The high reactivity of •OH and O radicals disrupts covalent bonds in lipids and proteins, initiating cell lysis and enzyme denaturation. Furthermore, nitrogen-based species contribute to peroxynitrite ($ONOO^-$) formation, enhancing bactericidal potency through nitration of tyrosine residues and oxidative DNA damage (Bhatia et al., 2021).

**9.2 Disruption of Microbial Cell Membranes:**

The microbial cell envelope—comprising the cell wall, plasma membrane, and outer membrane (in Gram-negative bacteria)—is the primary target for CP-induced damage. ROS and RNS attack unsaturated lipids, causing lipid peroxidation, which compromises membrane integrity and leads to leakage of intracellular contents (Misra et al., 2021).

Danilova et al. (2022) reported that air plasma treatment caused visible pits and pores on Listeria monocytogenes cell membranes as observed via scanning electron microscopy, confirming structural breakdown. In Gram-negative bacteria, plasma-generated ROS disrupt the outer lipopolysaccharide layer, while in Gram-positive bacteria, thick peptidoglycan walls are gradually eroded. The electrostatic interaction between charged plasma particles and negatively charged microbial surfaces enhances species adherence, amplifying oxidative attack (Liao et al., 2024).

Additionally, the electric field component of CP induces temporary membrane permeabilization similar to electroporation, facilitating further penetration of reactive species. This dual mechanism—chemical oxidation and physical disruption—ensures rapid and irreversible cell death (Bourke & Keener, 2022).

**9.3 DNA and Protein Oxidation:**

Cold plasma exposure results in significant nucleic acid degradation due to ROS-mediated oxidative stress and UV-induced photolysis. Thirumdas et al. (2020) demonstrated that plasma treatment of E. coli DNA led to strand fragmentation and base oxidation, with the formation of 8-oxoguanine—a key biomarker of oxidative DNA damage. The UV photons emitted from plasma, typically in the range of 200–280 nm, induce thymine dimer formation, inhibiting DNA replication and transcription (Misra et al., 2019).

Protein oxidation is another critical mechanism of microbial inactivation. Plasma-generated •OH radicals and ozone react with amino acid side chains (particularly cysteine, methionine, and tyrosine), leading to structural unfolding and aggregation. Pankaj et al. (2021) reported that exposure to argon plasma caused >60% reduction in microbial enzyme activity due to carbonylation of protein residues and disruption of tertiary structure. These oxidative modifications ultimately impair essential metabolic functions and enzymatic catalysis, leading to cellular apoptosis.

**9.4 Enzyme Inactivation Pathways in Food Systems:**

In addition to microbial enzymes, endogenous food enzymes—such as polyphenol oxidase (PPO), peroxidase (POD), lipase, and amylase—can also be inactivated by CP. Enzyme inactivation mechanisms primarily involve oxidation of amino acid residues, cleavage of peptide bonds, and alteration of active site geometry (Liao et al., 2024). Bhatia et al. (2021) found that plasma treatment reduced PPO activity in apple juice by 85%, attributed to conformational unfolding and oxidation of copper ions at the catalytic site. Similarly, Misra et al. (2021) demonstrated that cold plasma exposure caused irreversible denaturation of lipase in milk due to oxidation of sulfhydryl (-SH) groups and loss of α-helix content. Spectroscopic studies using circular dichroism (CD) and Fourier-transform infrared (FTIR) analysis confirm secondary structure alterations (α-helix → β-sheet transitions) following plasma exposure. These structural disruptions prevent proper substrate binding, leading to permanent loss of enzymatic activity. The ability of CP to selectively inactivate enzymes without heat makes it ideal for retaining nutritional and sensory properties in minimally processed foods (Thirumdas et al., 2020).

**9.5 Reactive Species–Matrix Interactions:**

The effectiveness of plasma-induced inactivation is also influenced by the composition and structure of the food matrix. Proteins, lipids, and polysaccharides can act as radical scavengers, moderating the effects of plasma treatment. Yildirim et al. (2022) observed that high-fat matrices (such as dairy products) showed lower microbial reduction due to radical quenching by lipids. Similarly, sugars and antioxidants like ascorbic acid neutralize reactive species, requiring optimization of exposure parameters for each food type (Bourke & Keener, 2022). However, certain interactions can be beneficial. Plasma treatment may lead to the formation of mild oxidation products that enhance flavor or improve texture in foods such as meats and bakery products. Controlled oxidation of lipids and proteins can also improve emulsification or gelation properties, contributing to texture enhancement (Misra et al., 2021).

**9.6 Reactive Nitrogen Species and Biofilm Disruption:**

Reactive nitrogen species (RNS) such as nitric oxide (NO) and nitrogen dioxide ($NO_2$) play a crucial role in disrupting microbial biofilms, which are typically resistant to conventional sanitization. Liao et al. (2024) demonstrated that plasma treatment reduced Pseudomonas fluorescens biofilm biomass by 95% through nitration of extracellular polymeric substances (EPS). RNS penetrate biofilm layers, inducing oxidative degradation of polysaccharides and proteins, which weakens the structural matrix and facilitates microbial detachment. The combination of RNS and ROS thus enhances biofilm eradication efficiency, making plasma particularly effective in cleaning surfaces and food contact equipment (Bhatia et al., 2021).

**9.7 Molecular-Level Modelling and Spectroscopic Insights:**

Recent studies employing electron paramagnetic resonance (EPR) and mass spectrometry have elucidated specific oxidative modifications in plasma-treated biomolecules. For example, Danilova et al. (2022) reported the formation of aldehyde and carbonyl derivatives of fatty acids following plasma exposure, confirming lipid oxidation pathways. Computational models, including molecular dynamics (MD) simulations, have further demonstrated that ROS can penetrate lipid bilayers within nanoseconds, initiating chain oxidation cascades (Xia et al., 2023). These molecular insights support the design of tailored plasma systems capable of selective inactivation of microorganisms and enzymes without excessive oxidation of food components. Advanced modeling approaches also allow prediction of reaction kinetics, aiding process control and ensuring product safety.

**9.8 Summary of Mechanistic Understanding:**

In essence, microbial and enzymatic inactivation by cold plasma involves a multi-target, multi-mechanism process comprising:

- Oxidative stress from ROS and RNS (chemical damage)
- UV-induced DNA photolysis (physical damage)
- Electric field–driven electroporation (mechanical disruption)
- Enzyme oxidation and conformational alteration (biochemical inactivation)

The intricate interplay of these mechanisms enables plasma to achieve broad-spectrum decontamination and enzymatic control while preserving food integrity. As analytical and computational tools evolve, deeper molecular understanding will allow for precision plasma processing, tailored to specific food matrices and microbial targets (Misra et al., 2019; Bourke & Keener, 2022).

## 10. Challenges, Industrial Implementation, and Future Research Directions in Cold Plasma Food Processing:

Cold plasma (CP) technology has shown remarkable potential as a non-thermal, sustainable, and highly effective food preservation tool, yet its transition from laboratory-scale studies to industrial adoption remains limited. While numerous studies validate its microbial safety, enzymatic control, and product quality retention, the technology still faces technical, regulatory, and economic barriers before large-scale commercialization can be achieved (Misra et al., 2019; Bourke & Keener, 2022). This section outlines key challenges, industrial applications, and emerging research directions shaping the future of cold plasma in the food sector.

### 10.1 Scalability and Reactor Design Challenges:

The foremost challenge in industrial implementation is the scaling-up of plasma reactors to treat high-throughput food systems uniformly. Laboratory systems such as dielectric barrier discharge (DBD) and plasma jets operate effectively on small samples, but ensuring uniform reactive species distribution over large or irregular surfaces is difficult (Thirumdas et al., 2020). According to Yildirim et al. (2022), uneven plasma exposure can lead to non-uniform microbial inactivation, affecting product safety and shelf-life consistency. Furthermore, reactive species like ozone, hydroxyl radicals, and nitrogen oxides have short lifetimes, demanding precise control of treatment distances and times. The design of continuous-flow and in-package plasma systems remains an active research area, focusing on optimizing electrode geometry, gas flow dynamics, and energy coupling efficiency (Bhatia et al., 2021). Computational fluid dynamics (CFD) models are increasingly employed to simulate plasma–gas–food interactions and ensure uniformity across industrial processing lines (Xia et al., 2023).

### 10.2 Energy Efficiency and Economic Considerations:

Although CP is classified as a low-temperature process, its energy requirements can vary significantly depending on discharge type, feed gas composition, and power supply frequency. Bourke & Keener (2022) highlighted that DBD systems operating at 50–100 W per liter of air can consume substantial energy when scaled for continuous industrial operations.

However, energy recovery systems and hybrid plasma configurations—combining CP with ultrasound or mild heat—have demonstrated up to 30% energy savings (Liao et al., 2024).

Economic analyses by Misra et al. (2021) show that plasma-based decontamination could be cost-competitive with thermal pasteurization if continuous-flow modules and optimized electrode designs are implemented.
Furthermore, plasma systems can operate on ambient air or nitrogen, eliminating the need for expensive inert gases, thereby reducing operating costs and improving sustainability metrics. Life Cycle Assessment (LCA) studies suggest that plasma technology produces significantly lower carbon footprints than conventional heat sterilization methods (Sharma et al., 2023).

**10.3 Process Optimization and Control:**

Process optimization is complex because plasma efficacy depends on multiple interrelated parameters, including input power, gas type, exposure time, humidity, and electrode distance. Modern approaches are moving toward data-driven optimization using machine learning (ML) and artificial intelligence (AI) models to predict microbial reduction and quality outcomes under varying conditions (Xia et al., 2023).
Bhatia et al. (2021) developed an AI-based predictive framework that correlated plasma treatment parameters with microbial survival curves, achieving 95% accuracy. Such adaptive control systems are crucial for achieving repeatable, safe, and energy-efficient plasma treatments. Integration of real-time sensors for reactive species concentration, temperature, and humidity further enhances process control and automation potential.

**10.4 Product-Specific Customization:**

Each food category—liquid, solid, or semi-solid—requires tailored plasma configurations due to differences in surface texture, composition, and conductivity. For instance, liquid foods benefit from plasma-activated water (PAW) systems, while solid foods such as fruits, vegetables, and meats are better suited for surface DBD or atmospheric plasma jets (Danilova et al., 2022). In high-fat or protein-rich foods, radical quenching can reduce microbial inactivation efficiency; thus, plasma exposure must be complemented with modified atmosphere packaging or vacuum systems to sustain RONS activity (Misra et al., 2019). Moreover, post-treatment chemical stability of sensitive nutrients (e.g., vitamins and polyphenols) must be assessed to ensure nutritional quality retention (Thirumdas et al., 2020).

**10.5 Regulatory and Safety Frameworks:**

One of the critical barriers to commercialization is the absence of harmonized international regulations governing plasma-treated foods. While countries like Japan and Germany have approved specific plasma sterilization systems for packaging materials, most regulatory agencies—including the U.S. FDA and European Food Safety Authority (EFSA)—require extensive safety data before approving food applications (Bourke & Keener, 2022).
Concerns primarily involve potential chemical residue formation, such as nitrite accumulation or oxidative by-products, and their long-term toxicological effects. However, studies by Liao et al. (2024) and Misra et al. (2021) have shown negligible migration of plasma-generated species into food matrices when optimized conditions are used.
To accelerate approval, a standardized evaluation protocol is needed—incorporating toxicity testing, residue monitoring, and microbiological validation—to ensure consistent safety assurance across global markets.

**10.6 Industrial Applications and Success Stories:**

Despite these challenges, several pilot-scale and commercial plasma systems have emerged. Freshline Plasma System (Air Products, UK) and Plasmatreat GmbH (Germany) have developed industrial DBD and plasma jet systems for decontaminating fresh produce, meat surfaces, and packaging films. Danilova et al. (2022) reported that in-package plasma sterilization of fresh-cut salads extended shelf life by 14 days without sensory degradation. Similarly, plasma-activated water is now commercially applied for surface sanitation in dairy plants and ready-to-eat meat facilities (Bhatia et al., 2021).

Emerging continuous conveyor-type plasma systems allow seamless integration into food lines, sterilizing surfaces and packaging before sealing. The eco-friendliness, low energy demand, and absence of chemical residues make plasma ideal for industries seeking clean-label and sustainable processing solutions.

**10.7 Environmental and Sustainability Aspects:**

Cold plasma aligns strongly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Its chemical-free operation, reduced energy footprint, and low water usage position it as a green alternative to chemical disinfectants and thermal pasteurization (Sharma et al., 2023). Additionally, plasma can be powered by renewable energy sources, and waste-free operation ensures minimal environmental pollution. When integrated with biodegradable or recyclable packaging materials, plasma processing supports a circular economy approach within the food industry (Yildirim et al., 2022).

**10.8 Future Research Directions:**

Future developments in cold plasma food technology will focus on several key areas:

1. **Reactor Miniaturization and Portability:** Development of compact, portable plasma units for on-site disinfection, farm-level decontamination, and supply chain sterilization.
2. **Smart Plasma Systems:** Integration of AI algorithms for adaptive control of plasma dose, exposure time, and RONS generation.
3. **Combination with Biobased Preservatives:** Synergistic integration with natural antimicrobials, essential oils, or biopolymers to enhance clean-label preservation.
4. **Mechanistic Understanding:** Advanced in situ spectroscopy and computational modeling to map plasma–biomolecule interactions in real time.
5. **Regulatory Harmonization:** Establishment of standardized international safety frameworks for plasma-treated foods and materials.
6. **Sustainability Metrics:** Detailed LCA and techno-economic assessments to quantify environmental and economic benefits at industrial scales.

Liao et al. (2024) suggest that combining plasma with renewable energy and sensor-enabled process control will pave the way for autonomous, intelligent, and low-carbon food manufacturing systems.

**10.9 Concluding Perspective:**

Cold plasma technology represents a paradigm shift in food preservation—offering an eco-friendly, energy-efficient, and residue-free alternative to conventional thermal and chemical methods. While challenges persist in scalability, regulatory acceptance, and process optimization, rapid advances in engineering design, hybrid technologies, and digital control are steadily bridging the gap between laboratory research and industrial adoption (Bourke & Keener, 2022). With continued innovation, interdisciplinary collaboration, and regulatory harmonization, cold plasma is poised to become a cornerstone of next-generation sustainable food processing and preservation systems—ensuring global food safety, extending shelf life, and reducing environmental impact in the 21st century and beyond (Misra et al., 2019; Thirumdas et al., 2020).

**11. Conclusion and Future Outlook:**

Cold plasma technology has rapidly evolved into one of the most promising non-thermal food processing and preservation platforms of the 21st century, bridging the gap between microbial safety, nutritional retention, and environmental sustainability. As demonstrated across a wide spectrum of studies, cold plasma's ability to generate reactive oxygen and nitrogen species (RONS) under atmospheric or low-pressure conditions enables efficient inactivation of pathogenic and spoilage microorganisms without significant heat input or chemical additives. This unique advantage positions cold plasma as a sustainable alternative to traditional preservation methods such as pasteurization, chlorination, or fumigation, which often compromise food quality or raise environmental concerns.

From the evidence synthesized in this review, it is evident that cold plasma extends far beyond microbial decontamination. The technology offers multi-dimensional benefits that include enzyme inactivation, detoxification of pesticide residues, improvement in surface wettability of packaging materials, and enhanced retention of sensory and nutritional attributes. For instance, plasma treatments have shown to effectively suppress enzymatic browning in fruits and vegetables, reduce lipid oxidation in meat and seafood, and prolong the shelf life of dairy and liquid foods while maintaining consumer-acceptable characteristics (Tolouie et al., 2018; Kim et al., 2020; Danilova et al., 2022). Moreover, the versatility of plasma devices—ranging from dielectric barrier discharge (DBD) systems to plasma jets—enables their adaptation across multiple sectors of the food chain, from raw produce handling to ready-to-eat packaging lines (Misra et al., 2021; Kumar et al., 2022). A major highlight of emerging research is the integration of plasma technology with sustainable and intelligent food systems. Plasma-modified biopolymers and coatings have enhanced antimicrobial activity and barrier functionality, thus facilitating active and intelligent packaging strategies aligned with green manufacturing goals (Bhatia et al., 2021; Agarwal et al., 2023). The advent of in-package plasma systems, which allow microbial decontamination of sealed food items, represents a paradigm shift toward closed-loop, residue-free preservation methods (Arjmand et al., 2024). When coupled with renewable power sources and AI-based process optimization tools, these systems have the potential to significantly lower the environmental footprint of food manufacturing (Xia et al., 2023; Liao et al., 2024). Despite these achievements, industrial-scale implementation of cold plasma faces notable challenges. Variability in plasma discharge characteristics, non-uniform treatment distribution, and potential oxidative damage to sensitive compounds remain technical barriers to commercialization (Dobrynin et al., 2021). Moreover, the absence of standardized regulatory frameworks across different countries has limited the approval and labeling of plasma-treated foods. As noted by EFSA (2021), comprehensive risk assessments on potential by-products, residue safety, and consumer perception are critical before broad-scale adoption. Continued interdisciplinary collaboration among plasma physicists, food technologists, and policymakers will therefore be vital to translate laboratory findings into real-world processing systems. Looking ahead, the future trajectory of cold plasma research lies in developing hybrid preservation platforms—combining plasma with pulsed electric fields, UV-C, ultrasound, or mild heating—to achieve synergistic microbial reduction while minimizing oxidative stress (Martillanes et al., 2022). The integration of plasma with Internet of Things (IoT)-enabled sensors for real-time control of voltage, gas flow, and exposure time could enable predictive safety modeling and automation in food production (Xia et al., 2023). Additionally, plasma-activated water (PAW) is emerging as an eco-friendly sanitizer with wide applications in both food contact surfaces and washing of fresh produce (Sakai et al., 2023).

In conclusion, cold plasma technology stands at the forefront of next-generation sustainable food preservation systems, offering a unique combination of microbiological safety, nutritional retention, and environmental stewardship. Its non-thermal nature, adaptability, and chemical-free operation resonate strongly with the principles of circular economy and green processing. However, to unlock its full industrial potential, concerted efforts must focus on scaling, standardization, regulatory validation, and consumer education. By integrating plasma science with smart digitalization, renewable energy, and biodegradable materials, the food industry can move toward a future-ready preservation paradigm—one that ensures food safety, reduces waste, and contributes to global food security in an environmentally responsible manner.

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