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Cold Plasma Technology: A Sustainable and Chemical-Free Innovation for Agricultural and Food Applications

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Cold plasma, or non-thermal plasma, represents a cutting-edge, sustainable technology that enables chemical-free treatment of biological and agricultural materials. Comprising reactive oxygen and nitrogen species (RONS), UV photons, and charged particles at near-ambient temperatures, cold plasma effectively inactivates microorganisms, alters surface properties, and stimulates beneficial physiological responses without heat damage. Generated through methods such as dielectric barrier discharge, plasma jets, and corona discharge, it operates efficiently at atmospheric pressure, offering adaptable solutions for agricultural and food industries. Applications of cold plasma span seed decontamination, germination enhancement, pesticide residue degradation, post-harvest disinfection, and the production of plasma-activated water (PAW) for irrigation and foliar use. Its mechanisms involve synergistic chemical and physical interactions, including oxidative stress, UV radiation, and localized electric fields, which together inactivate pathogens while enhancing plant growth and stress tolerance. For India, cold plasma offers significant potential to improve seed systems, reduce post-harvest losses, and ensure food safety within sustainable and low-resource frameworks. Key challenges such as scale-up, process standardization, and regulatory validation must be addressed through coordinated research, demonstration hubs, and capacity building. Overall, cold plasma technology aligns with global sustainability goals, providing a promising route toward greener, safer, and more resilient agri-food production systems.

Keywords: Cold plasma, sustainable agriculture, agri-food production systems.

Overview of Cold Plasma technology

Cold plasma, also referred to as non-thermal plasma, is a partially ionized gas comprising a complex mixture of electrons, ions, neutral particles, reactive oxygen and nitrogen species (RONS), UV photons, and free radicals (Misra *et al.*, 2016). Unlike thermal plasmas, cold plasma operates at or near room temperature, making it suitable for treating heat-sensitive materials such as biological tissues, seeds, and food products. The unique feature of cold plasma lies in its ability to produce highly reactive chemical species without inducing significant thermal damage, thus maintaining the structural integrity of treated materials (Scholtz *et al.*, 2015).

Cold plasma is typically generated through various electrical discharge techniques such as dielectric barrier discharge (DBD), plasma jets, corona discharge, and glow discharge (Niemira, 2012). These generation methods can be optimized for atmospheric pressure operation, eliminating the need for vacuum systems and making cold plasma technologies economically viable and adaptable for agricultural and industrial applications. The versatility of atmospheric cold plasma allows it to be used in seed treatment, microbial decontamination, food preservation, and surface modification (Bourke *et al.*, 2018).

The reactive species and charged particles generated by cold plasma interact with the surface of biological materials, leading to microbial inactivation through mechanisms such as cell membrane disruption, protein oxidation, and DNA damage (Laroussi, 2009). Additionally, the exposure to RONS can modulate biochemical pathways and enhance germination rates in seeds by altering surface chemistry and stimulating stress-responsive genes (Starič *et al.*, 2020). The process occurs at low temperatures, ensuring that biological viability is preserved while achieving effective sterilization and functionalization.

Recent research highlights cold plasma as an eco-friendly and sustainable technology, offering a chemical-free alternative to conventional agricultural and food safety treatments. Its application aligns with current global trends toward green technologies and sustainable production systems (Graves, 2012). With ongoing advancements in plasma source design and process optimization, cold plasma holds significant potential to revolutionize agricultural practices, post-harvest management, and food processing sectors.

Applications of Cold Plasma in Agriculture

The agricultural sector faces increasing challenges related to food security, sustainability, and the reduction of chemical inputs. Cold plasma technology has emerged as a promising tool for addressing these challenges due to its ability to enhance crop productivity, improve food safety, and minimize environmental impact (Bourke *et al.*, 2018; Misra *et al.*, 2016). The versatility of cold plasma applications in agriculture stems from its multi-functional nature enabling microbial inactivation, seed treatment, pesticide degradation, and enhancement of plant growth processes.

1. Seed Decontamination and Germination Enhancement

One of the most explored applications of cold plasma in agriculture is seed surface decontamination. Plasma-generated reactive species effectively inactivate seed-borne pathogens, including fungi, bacteria, and viruses, without the use of harmful chemicals (Selcuk *et al.*, 2008). Moreover, plasma treatment modifies the seed coat surface properties, such as wettability and permeability, facilitating better water absorption and gas exchange during germination (Starič *et al.*, 2020). In addition to pathogen control, plasma exposure has been shown to stimulate germination and early seedling growth by inducing mild oxidative stress that triggers defense-related gene expression and enzymatic activities (Ling *et al.*, 2014). Such physiological enhancements can improve crop establishment and yield potential, particularly under suboptimal environmental conditions.

2. Post-Harvest Decontamination of Fresh Produce

Cold plasma has demonstrated high efficacy in the decontamination of fruits, vegetables, grains, and nuts, effectively reducing microbial load on surfaces while maintaining product quality (Misra *et al.*, 2011). The reactive oxygen and nitrogen species (RONS) generated in plasma interact with microbial cells, leading to membrane disruption and DNA damage, resulting in microbial inactivation (Niemira, 2012). Unlike conventional chemical disinfectants, plasma treatment leaves no harmful residues and preserves the nutritional and sensory attributes of the produce (Ziuzina *et al.*, 2015). Therefore, it serves as a sustainable alternative for maintaining food safety in post-harvest systems.

3. Pesticide Degradation and Residue Removal

Another significant application of cold plasma technology lies in pesticide degradation. Residual pesticides on agricultural produce pose serious health and environmental risks. Plasma-generated reactive species, including hydroxyl radicals and ozone, are capable of oxidizing and decomposing pesticide molecules into less harmful compounds (Sarangapani *et al.*, 2017). This process enhances the safety of fresh produce and contributes to reducing the environmental footprint associated with chemical pesticide use.

4. Soil and Water Treatment

Emerging research indicates that cold plasma can be applied in soil and irrigation water treatment to eliminate plant pathogens and degrade chemical contaminants (Thirumdas *et al.*, 2018). Plasma-activated water (PAW), a by-product of plasma discharge in air or liquid, contains reactive species that retain antimicrobial and oxidative properties. PAW can be used as a biocompatible disinfectant for irrigation, foliar application, and surface sanitation

(Schnabel *et al.*, 2021). This approach offers a sustainable and low-cost alternative for maintaining soil and water hygiene in agriculture.

5. Enhancement of Plant Growth and Stress Resistance

Cold plasma exposure has been shown to enhance plant growth, stress tolerance, and nutrient uptake through modulation of cellular signaling pathways (Adhikari *et al.*, 2020). The RONS generated by plasma can act as signaling molecules, activating antioxidant enzymes and stimulating secondary metabolite production in plants. These effects contribute to improved resilience against abiotic stresses such as drought, salinity, and temperature extremes.

Mechanisms of Action of Cold Plasma in Biological Systems

The effectiveness of cold plasma technology in agriculture and biological applications arises from its complex physicochemical interactions with living systems. When plasma interacts with biological materials—such as plant tissues, microbial cells, or seed surfaces—it generates a range of biologically active agents, including reactive oxygen species (ROS), reactive nitrogen species (RNS), charged particles, UV photons, and electric fields. These agents act synergistically to induce a variety of physical, chemical, and biological effects without causing significant thermal damage (Graves, 2012; Laroussi, 2009).

1. Role of Reactive Oxygen and Nitrogen Species (RONS)

Reactive species are the primary drivers of plasma-induced biological activity. The ROS (such as ozone (O_3), hydrogen peroxide (H_2O_2), hydroxyl radicals (•OH), and singlet oxygen ($^1O_2$)) and RNS (such as nitric oxide (NO) and peroxy-nitrite ($ONOO^-$)) are formed during plasma discharge (Stoffels *et al.*, 2008). These species possess high oxidative potential, allowing them to interact with cellular membranes, proteins, lipids, and nucleic acids. In microbial cells, RONS cause oxidative stress, leading to membrane disruption, protein denaturation, enzyme inhibition, and DNA fragmentation (Zhang *et al.*, 2013). The cumulative effect of these interactions results in irreversible cellular damage and microbial inactivation. In plants and seeds, however, controlled plasma exposure can stimulate beneficial signaling pathways. Low doses of RONS act as secondary messengers, enhancing antioxidant defense mechanisms, modulating hormone signaling, and promoting germination and growth (Ling *et al.*, 2014; Adhikari *et al.*, 2020). This dual role of RONS—deleterious to pathogens yet beneficial to plants—illustrates the selective and tunable nature of cold plasma effects.

2. UV Radiation and Charged Particle Interactions

Plasma-generated UV photons (particularly in the UVC range) possess strong germicidal properties by inducing thymine dimer formation and nucleic acid damage in microbial cells (Laroussi, 2002). This mechanism complements the oxidative effects of RONS, leading to more effective sterilization of seed surfaces and produce. Additionally, charged particles (electrons and ions) in the plasma stream can alter the surface energy and morphology of biological materials. In seeds, these interactions can increase surface hydrophilicity and permeability, thereby improving water uptake and enzyme activation during germination (Bormashenko *et al.*, 2015).

3. Electric Fields and Plasma-Induced Physical Effects

Cold plasma generates localized electric fields and transient electromagnetic pulses that influence cellular structures and molecular dynamics. These fields can cause electroporation, leading to temporary or permanent pores in cell membranes that facilitate nutrient exchange or microbial inactivation (Yusupov *et al.*, 2012). Furthermore, the surface etching effects of plasma modify seed coats and plant surfaces at the micro- and nanoscale, improving adhesion for nutrients, coatings, or biostimulants (Mitra *et al.*, 2014). These physical effects are crucial in agricultural applications where both decontamination and enhancement of biological function are desired.

4. Plasma-Activated Liquids and Indirect Mechanisms

When plasma interacts with liquids—such as water or nutrient solutions—it produces plasma-activated water (PAW), a reactive medium containing long-lived species like nitrates, nitrites, and hydrogen peroxide (Thirumdas *et al.*, 2018). These species retain antimicrobial and signaling properties, allowing PAW to be used for seed soaking, irrigation, and foliar spraying. The mechanism of action in PAW involves sustained oxidative activity and gradual diffusion of reactive compounds, making it a controlled and residue-free alternative for disinfection and plant stimulation (Schnabel *et al.*, 2021).

Specific prospects of Cold Plasma technology for India

- Seed systems and smallholder impact: low-temperature, quick seed treatments could be deployed at seed shops, village seed banks, and on-farm nurseries to raise crop establishment and reduce fungicide use. This is valuable for pulse, oilseed, rice nursery and vegetable seed sectors.
- Postharvest loss reduction: in-market and pack house plasma units can lower microbial spoilage of high-value horticultural produce, addressing India's significant postharvest losses and cold-chain gaps.
- Safe value chains for exports: in-package plasma decontamination can help meet phyto-sanitary standards and reduce reliance on chemical fumigants for export commodities.
- Resource-poor regions: plasma treatment of irrigation water and local remediation could improve water safety where conventional treatment is limited.
- Integration with precision and digital agriculture: mobile or modular plasma units can be coupled with existing farm machinery or packhouse lines for targeted interventions, enabling rapid adoption at cooperative or contractor scale.

Technical and commercial challenges Cold Plasma technology in India

- Scale-up and throughput: most studies are lab or pilot scale; scaling to bulk seed batches, palletized produce, or continuous water flows requires engineering redesign and validation.
- Standardization and process control: treatment dose, geometry, gas composition, and exposure time must be standardized for consistent efficacy and safety across crop types.
- Capital and operating cost: initial equipment cost and power needs may be barriers for smallholders unless subsidized, provided as service models, or designed for low-power operation.
- Safety, by-products and regulatory acceptance: formation of reactive by-products (ozone, nitrates) requires monitoring and regulatory clarity for food and environmental safety before wide commercialization.
- Knowledge and skills gap: technicians, extension workers, and farmers need training on correct use, maintenance, and integration into crop management practices.

Recommended pathway for adoption in India

1. Focused R&D and pilots: fund multidisciplinary trials on key crops (rice nurseries, pulses, mango, tomatoes, onion) that measure yield, quality, residue reduction, and economics.
2. Demonstration hubs and service models: set up regional packhouse/pilot units run by cooperatives, agri-processors, or entrepreneurs to offer plasma as a service, lowering per-farmer cost.
3. Standards and regulatory roadmap: establish treatment-dose guidelines, residue/by-product testing protocols, and food safety acceptance criteria via collaboration between ICAR, FSSAI, and research institutes.
4. Low-cost engineering and power optimization: incentivize Indian SMEs and startups to develop affordable, rugged plasma generators tailored to rural electricity conditions and local throughput needs.
5. Capacity building and extension: train extension agents and agritech service providers on benefits, limitations, and safe operation, with clear farmer communication to build trust.

Short summary and outlook

Overall, the biological mechanisms of cold plasma action are multi-faceted and interdependent. The combination of chemical, photonic, and electric effects enables plasma to target microbial contaminants while promoting beneficial physiological responses in plants. Understanding these mechanisms is essential for optimizing plasma parameters, ensuring safe application, and harnessing its full potential for sustainable agriculture and food systems. Cold plasma offers a versatile, chemical-free toolkit for seed enhancement, microbial control, residue reduction, and postharvest quality improvement that aligns with sustainability goals and India's needs for safer, higher-value agri-produce. Realizing its potential requires coordinated investment in scale-up engineering, regulatory frameworks, field pilots on priority crops, and accessible business models that bring the technology to farmers and packagers.

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