PLANT SCIENCE TODAY
Vol 12(sp1): 01-10
https://doi.org/10.14719/pst.7993

eISSN 2348-1900

REVIEW ARTICLE

Cold plasma: A green technology for improving legume productivity

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Received: 28 February 2025; Accepted: 26 July 2025; Available online: Version 1.0: 25 September 2025

Cite this article: Anu, Manonmani V, Jerlin R, Vanitha S, Sivakumar R, Preetha G, Rashmi J. Cold plasma: A green technology for improving legume productivity. Plant Science Today. 2025;12(sp1):01-10. https:/doi.org/10.14719/pst.7993

Abstract

Cold plasma technology represents a groundbreaking innovation in sustainable agriculture, particularly for optimizing the germination dynamics, physiological vigor and resilience of leguminous crops. As a non-thermal ionized gas, cold plasma induces intricate physicochemical modifications in seed architecture, enhancing surface hydrophilicity, permeability and imbibition kinetics. These transformations expedite germination, activate key enzymatic cascades and fortify antioxidative defense mechanisms, thereby bolstering legume adaptation to environmental stressors. Furthermore, cold plasma has been shown to regulate gene networks associated with stress tolerance, nitrogen assimilation and metabolic efficiency, culminating in improved plant vigor and yield stability. Beyond seed enhancement, cold plasma serves as an eco-compatible strategy for microbial decontamination, effectively neutralizing phytopathogens on legume seeds without compromising viability. It also extends post-harvest longevity by mitigating spoilage and oxidative degradation. Recent advancements have leveraged cold plasma in synergy with nanotechnology to facilitate targeted nutrient delivery, while its integration with magnetic field exposure has demonstrated enhanced metabolic activation and water absorption in leguminous seeds. Additionally, machine learning applications are refining plasma treatment protocols, enabling precise optimization tailored to specific crop requirements. As a transformative and environmentally sustainable agronomic tool, cold plasma holds profound implications for advancing legume cultivation while reducing reliance on chemical inputs. Its capacity to enhance seed vigor, stress tolerance and crop productivity underscores its potential as a pivotal innovation in climate-resilient, high-efficiency agricultural systems. Further exploration and technological refinement will unlock new frontiers, establishing cold plasma as a cornerstone of modern legume agronomy.

Keywords: cold plasma; germination; legumes; nanotechnology; nodulation

Introduction

Cold plasma (CP), a non-thermal ionized gas composed of reactive oxygen and nitrogen species (RONS), has emerged as a promising seed treatment technology that enhances germination, seedling vigor and stress tolerance while reducing pathogen load and chemical residues (1). Unlike conventional priming methods such as hydro-priming and chemical priming, CP treatment is rapid, residue-free and environmentally sustainable (2). CP generates reactive species, including atomic oxygen (O), ozone (O_3), hydroxyl radicals (OH), nitric oxide (NO) and hydrogen peroxide (H_2O_2), which interact with seed surfaces, modifying surface chemistry, increasing wettability and improving water uptake (3, 4). These interactions trigger biochemical signaling cascades that stimulate enzymatic activity and metabolic responses, ultimately enhancing germination and early seedling development (5, 6).

Legumes play a pivotal role in sustainable farming by forming symbiotic associations with rhizobia, enabling biological nitrogen fixation (BNF), which enriches soil fertility, reduces reliance on synthetic fertilizers and enhances crop performance in intercropping systems (7). Their integration into cropping systems improves nutrient availability, soil structure and microbial activity while disrupting pest cycles. However, excessive nitrogen fertilization has led to severe environmental consequences, including soil acidification, water pollution and greenhouse gas emissions (8, 9). Therefore, novel strategies that enhance legume nitrogen assimilation and optimize seed performance are critical for sustainable agricultural intensification. In legumes, CP has demonstrated potential in improving nodulation and BNF, key processes that enhance soil fertility and reduce dependence on synthetic fertilizers and enhancing nitrogen use efficiency (NUE) in plants, which could significantly improve legume-based cropping systems by maximizing nitrogen fixation potential and reducing environmental nitrogen losses (10) and promote root nodulation in pea and lentil (11), improves seed germination under salinity stress (12), enhance nutrient uptake and seed vigor (13), eco-friendly microbial decontamination tool, reducing pathogen load while preserving seed viability (14, 15), induces bioactive compound synthesis in microgreens (16) (Fig. 1).

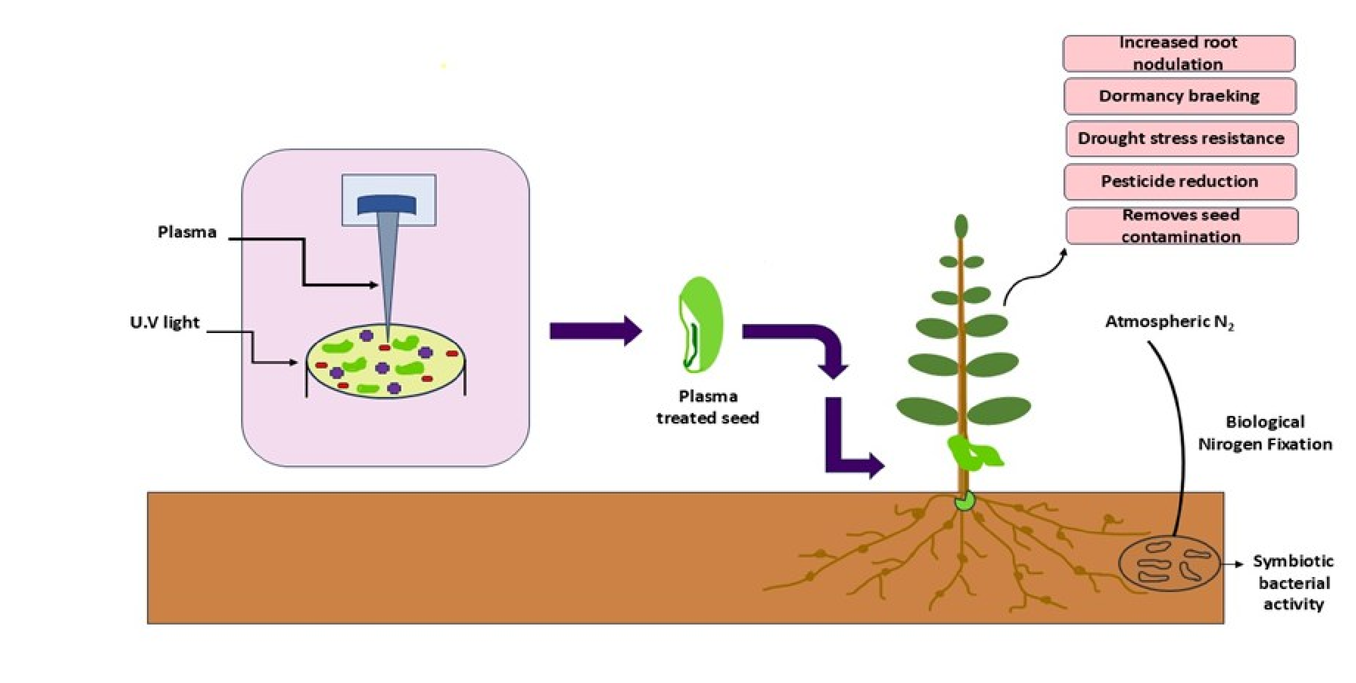

Fig 1. Role of plasma in legumes.

Despite its advantages, several challenges hinder the widespread adoption of CP technology. The effects of CP vary based on plasma source, treatment duration, feed gas composition, seed variety and environmental conditions, leading to inconsistencies in experimental outcomes (17). Additionally, the molecular mechanisms underlying CP-induced seed responses remain poorly understood and existing reviews fail to comprehensively address the latest experimental findings (10). There is also a need for standardized treatment protocols to ensure reproducibility across different crop species and environments. Scaling up CP technology for large-scale agricultural applications requires further research on cost-effectiveness, field applicability and integration with precision agriculture and automation (18, 19).

Objective of the review

CP, as an innovative technology, holds significant promise for advancing sustainable agriculture and requires further investigation. This review aims to bridge existing knowledge gaps by providing a comprehensive analysis of plasma-based technologies in legume cultivation. Specifically, it explores their role in enhancing germination, improving nodulation, increasing stress resilience and boosting overall productivity. By integrating these advanced approaches, modern agriculture can fully leverage the benefits of legumes, contributing to food security, environmental sustainability and economic development.

Review methodology

A thorough and extensive review of the literature on cold plasma treatment and its impact on leguminous crops was undertaken. A wide range of research articles and review papers from reputable databases, including ResearchGate, ScienceDirect, Google Scholar and Academia were meticulously analyzed to synthesize the findings presented in this review.

Plasma treatment

Plasma, the fourth fundamental state of matter, is an energetic and dynamic medium containing freely moving electrons, charged ions and reactive particles. It also includes neutral gas atoms and molecules in different energy states, emitting a wide range of radiation, including ultraviolet and vacuum ultraviolet light (20). CPs are artificially generated ionized gases, produced through low-frequency, radio frequency or microwave discharge at reduced pressures. They exhibit energy levels ranging from 1 to 10 eV and electron densities around 10^{10} cm^{-3}. Due to their low ionization degree ($<10^{-3}$, the gas phase is predominantly composed of excited neutral atoms and reactive radical species rather than charged particles (21). Throughout the ACP discharge process, the generation of electrons, ions and excited species induces interactions with the surrounding air, resulting in the formation of a range of RONS. These include O, O_3, OH, NO and H_2O_2, which are regarded as the principal reactive species (3). Over the past two decades, several types of plasma sources have been developed, including dielectric barrier discharge (DBD), jet plasma, microwave discharge, radiofrequency (RF) discharge and corona discharge. Seed germination has been found to fluctuate based on factors such as the type of plasma source, seed variety, treatment duration, feed gas and humidity levels (17).

Methods of plasma generation

A diverse array of plasma generation techniques has been utilized for CP production, with atmospheric pressure plasma (CAP), dielectric-barrier discharge (DBD), glow discharge, radio frequency discharge and corona discharge emerging as the most prevalent methodologies (22).

Cold atmospheric pressure plasma

CAP is generated by exposing gases such as air, oxygen, nitrogen, or noble gases like argon and helium to a high-voltage electrical discharge, resulting in the formation of an ionized state characterized by an intricate assembly of reactive free radicals, stable oxidizing species and ultraviolet (UV) radiation. The synergistic interplay of these components underpins CAP's potent antimicrobial properties, making it a versatile tool across biomedical, environmental and agricultural domains (23, 24). Recognized for its multifaceted bioactivity, CAP serves as a powerful inducer of biochemical transformations across bacterial, mammalian and plant cells, positioning it at the forefront of contemporary agricultural innovation (25). Its biological effects are governed by a sophisticated interaction of RONS, ionized particles, excited molecular species and UV photons, collectively orchestrating significant cellular responses (26). These findings underscore CAP's transformative potential in sustainable agriculture, offering an advanced, non-thermal strategy for improving seed quality, accelerating plant establishment and optimizing crop productivity.

Dielectric-barrier discharge (DBD)

DBD is an advanced plasma generation technique that produces visually distinct, diffuse plasma layers under atmospheric pressure in gases such as N_2, O_2 and Ar. Renowned for its versatility, DBD has been extensively utilized across various applications, with significant impact in the agricultural sector (27). In the context of seed enhancement, DBD air plasma treatment has demonstrated substantial improvements in black gram seed germination (13.67 %), seedling growth (37.13 %), chlorophyll biosynthesis (37.26 %) and biochemical composition, including soluble proteins (53.60 %) and sugars (51.71 %). This enhancement is attributed to the plasma-induced modification of nitrogenous complexes within the seed coat, facilitating increased protein synthesis and promoting overall plant vigor (28). A comparative evaluation of three cold atmospheric pressure plasma treatments on soybean seeds diffuse coplanar surface barrier discharge (DCSBD), multi-hollow surface dielectric barrier discharge and air plasma jet revealed DCSBD as the most effective technique. This approach enhanced germination efficiency while optimizing energy consumption and treatment duration. Plasma exposure also improved seed wettability and imbibition dynamics without significantly altering surface morphology (29). Similarly, DBD cold plasma treatment significantly promoted pea seedling growth, with plasma-activated tap water (PATW) and plasma-activated seeds (PAS) increasing germination rates and chlorophyll accumulation by over 50 %. The roles of H_2O_2 and nitrate were pivotal in mediating these growth enhancements, while plasma etching facilitated improved water absorption. This technique presents a sustainable and eco-friendly alternative to conventional chemical fertilizers, aligning with modern agricultural innovation (30).

Radio frequency discharge

A radio frequency plasma generation system operates through the coordinated function of a discharge unit, a ceramic nozzle, a grounded electrode and a gas supply mechanism. Equipped with a needle electrode and an active ring electrode, the nozzle generates a high capacity oscillating voltage, producing a powerful radiofrequency field. Functioning at 1 kW and 13.56 MHz, this system enables efficient ionization and plasma formation (31). In agricultural applications, cold radiofrequency air plasma has demonstrated the ability to enhance the hydrophilicity of *Phaseolus vulgaris* seeds, significantly accelerating water absorption, particularly through the micropyle. Although overall germination rates remained unchanged, plasma-treated seeds exhibited a more rapid germination process, underscoring its potential to improve early seedling development (32).

Corona discharges

Corona plasma is generated when a high-voltage electrical discharge occurs between electrodes with differing curvatures, such as a pointed pin and a flat plate or a thin wire and a plate. The concentrated electric field at sharp edges lowers the voltage threshold required for discharge initiation, facilitating stable and controlled plasma formation along the grounded electrode's surface (19). In agricultural applications, corona glow discharge plasma has been shown to enhance the growth performance of soybean black seeds. A 30 min plasma exposure led to a 71.38 % increase in stem length, a 3.27 % rise in leaf count, a 16.47 % expansion in leaf width and a remarkable 314.28 % enhancement in germination. These improvements are attributed to nitrogen ion absorption, which likely stimulated metabolic processes critical for early seedling development (33).

Glow discharge

Low frequency glow discharge (LFGD) plasma is a sophisticated non-thermal plasma technology, generated under controlled laboratory conditions at moderate pressure (~10 torr) through the application of high voltage at low frequency. Recognized for its efficiency, scalability and eco-friendly nature, LFGD plasma has been extensively investigated for its potential to enhance seed quality, accelerate seedling development and improve overall agricultural productivity (34). In legume cultivation, cold glow discharge plasma has been shown to enhance moisture absorption in chickpeas. Plasma treatment at 40-60 W for up to 20 min significantly improved water uptake after eight hours, with maximum absorption reaching 103.31 % in the Kripa variety and the lowest recorded at 79.44 % in Rajas. These findings underscore the role of plasma-induced surface modifications in optimizing seed hydration, a crucial factor for uniform germination and early seedling establishment (35).

Cold plasma treatment in legumes

Nodulation and biological nitrogen fixation in legumes

Legumes uniquely develop symbiotic root nodules with nitrogen-fixing bacteria to acquire nitrogen. This process synchronizes rhizobial infection in the epidermis with cortical cell division. Inside the nodules, symbiosomes enclose the bacteria, enabling nitrogen fixation and metabolite exchange with the host (36). Research has demonstrated that CP seed treatment enhances nodulation and BNF in pea (*Pisum sativum*) and lentil (*Lens culinaris*), leading to improved root development and increased shoot biomass (11). Similarly, plasma treatment of soybean seeds using O_2 or N_2 gases stimulated nodulation and nitrogen fixation. This treatment increased nitrogenase activity, leghaemoglobin content and nitrogen levels in both nodules and plants. Additionally, it enhanced key biometrical parameters while influencing root compounds and gene expression, positioning CP as a promising pre-sowing technique for optimizing soybean growth (37). As the demand for sustainable agricultural practices grows, cold plasma technology presents a novel, eco-friendly approach to enhancing legume productivity. By improving biological nitrogen fixation and plant development, CP treatment could contribute to reducing chemical fertilizer dependency and fostering more resilient cropping systems.

Ability to remove seed contamination

Leguminous plant species are susceptible to various seedborne diseases and because they are directly sown, they face a significant risk of infection (38). Low-pressure oxygen plasma improved *Phaseolus vulgaris* seed wettability, reducing fungal contamination and accelerating water uptake for better seedling establishment (39). Similarly, dielectric barrier discharge plasma using O_2 and N_2 enhanced *Glycine max* growth and yield while reducing pathogen incidence and oxidative stress (40). Plasma treatment improved *Pisum sativum* germination by 10-25 %, reinforcing cell walls through increased peroxidase activity and lignin accumulation (41).

Plasma-treated water (PTW) boosted *Vigna radiata* germination (95.5 %) and vigor while effectively reducing microbial contamination (42). CAP and plasma-activated water (PAW) further achieved a 2.5 log CFU/g microbial reduction in mung bean seeds without affecting viability (43). Non-thermal plasma controlled *Diaporthe/Phomopsis* fungi in soybean, improving seed quality by reducing oxidative damage and enhancing glutathione levels (44). Low-pressure cold plasma (LPCP) using SF_6 reduced fungal adhesion below 1 % while maintaining germination (45). Additionally, PAW combined with ultrasound increased antimicrobial efficacy, achieving a Log10 3.48 reduction in *Salmonella Montevideo* on seeds (46). Thus, plasma-based seed treatments present a sophisticated and sustainable approach to enhancing germination, vigor and pathogen resistance, underscoring their potential as a transformative innovation in agricultural science.

Dormancy breaking

Physical dormancy, caused by an impermeable seed coat, evolved as an adaptive trait but hinders uniform germination in agriculture. It remains a key target for breeding and domestication, especially in legumes (47). In *Vigna radiata*, plasma exposure accelerated germination 11-fold in 12 hrs and tripled radicle length in 96 hrs by improving water uptake and upregulating gibberellic acid (48). Similarly, low-pressure plasma enhanced *Desmanthus virgatus* seed germination and imbibition while reducing nutrient loss (49). In *Robinia pseudoacacia*, non-thermal plasma (NTP) treatment for 20 min significantly increased water absorption and seedling vigor, partially overcoming dormancy (50). CAP improved wettability in *Leucaena leucocephala*, though the macrosclereid layer remained resistant to water penetration (51). Low-pressure argon plasma at 40 °C successfully broke dormancy in *D. virgatus*, accelerating germination without altering chemical composition (52). These findings highlight plasma technology as a promising, sustainable alternative for improving seed germination and agricultural productivity.

Seed germination

Seed germination and plant growth are intricately linked to biochemical and physiological markers. H_2O_2 acts as a dynamic signaling molecule, exhibiting both promotive and inhibitory effects on plant development and stress resilience (53). Recent studies highlight the potential of plasma-based treatments, including CP, cold atmospheric pressure plasma (CAPP) and PAW, in improving seed hydrophilicity, enzymatic activity and stress tolerance, ultimately enhancing plant growth and yield. CP exposure has been shown to significantly enhance seed germination by modifying surface properties. In mung bean (*Vigna radiata*), plasma treatment improved hydrophilicity, increased enzymatic activity and reduced anti-nutritional factors, proving beneficial under drought stress (54). Similarly, short-term CAPP exposure (60 s) in air and nitrogen atmospheres significantly improved pea seed germination and enzymatic activity by enhancing surface wettability and activating antioxidant defense mechanisms (55). Guar bean (*Cyamopsis tetragonoloba*) also responded positively to CP treatment, with optimal conditions (20 kV, 90 s) promoting root elongation, chlorophyll synthesis and protein digestibility, although excessive exposure impaired germination (56). Hydrophilicity enhancement plays a central role in plasma-mediated germination improvement. Studies on *Phaseolus vulgaris* demonstrated that CP accelerated water absorption and seed germination without altering final germination rates (32, 57). Likewise, low-temperature plasma pretreatment in *Pisum sativum* activated enzymes and phytohormones, improving seed vigor and water uptake while modifying the seed surface for enhanced plasma ion-electron interactions (58). Alfalfa (*Medicago sativa*) seeds exhibited increased wettability due to plasma-induced surface modifications, as confirmed by XPS and SEM analyses (59). Furthermore, CP at 80 W increased soybean germination, seedling growth and water uptake, stimulating root elongation, seed reserve utilization and the accumulation of soluble sugars and proteins (60). Beyond legumes, plasma technology has demonstrated promising applications in various other crops. In *Vigna unguiculata* (long bean), brief plasma exposure (4 min) improved seed vigor, whereas prolonged treatment (> 6 min) proved detrimental (61). Additionally, cold plasma exposure in soybean influenced biochemical properties, increasing antioxidant enzyme activity while reducing polyphenol and flavonoid content, though radical scavenging capacity remained stable (62). Collectively, these studies underscore the transformative potential of plasma-based seed treatments in improving germination efficiency, seedling vigor and plant stress resilience. By modulating seed surface properties, enzymatic activity and metabolic pathways, CP and PAW offer sustainable and innovative strategies for optimizing agricultural productivity. However, future research should focus on fine-tuning plasma exposure parameters to balance beneficial effects with potential oxidative damage, ensuring maximal efficacy for different crop species.

Drought stress

Drought profoundly impacts various stages of legume growth and development, including germination, shoot and root formation, photosynthesis and reproduction. Intensified by global climate change, drought remains an unpredictable and uncontrollable constraint on crop production, exerting detrimental effects on legume yield and sustainability (63). Recent studies have explored cold plasma treatment as a promising approach to enhancing seed resilience under drought stress. A study on licorice seeds found that surface dielectric barrier discharge (SDBD) air plasma treatment significantly improved germination speed, efficiency and drought tolerance, outperforming argon gas treatment and demonstrating its potential for strengthening seedling resilience (64). Similarly, CP treatment enhanced alfalfa seed germination and growth under simulated drought conditions (0-15 % PEG 6000). Seeds treated at 40 W exhibited the highest vigor, with an increase of up to 74.34 %. Lower power levels improved germination, while higher levels had inhibitory effects, underscoring the importance of optimizing treatment parameters (65). In another study, CAP treatment at 30 seconds improved germination, growth and drought resistance in pea and zucchini seeds, whereas 60 sec of exposure reduced germination and seedling growth, further emphasizing the need for precise application (66). These findings highlight cold plasma technology as a promising tool for enhancing legume drought tolerance, supporting resilient cropping systems and stable yields in water-limited conditions (Table 1).

Pesticide reduction

Synthetic chemical-based pesticides disrupt symbiotic nitrogen fixation (SNF), thereby reducing nitrogen assimilation and increasing crop dependence on soil-available nitrogen. Consequently, declining soil fertility adversely impacts crop productivity and diminishes produce quality (67). Recent research has explored

Table 1. Effect of CP treatment in leguminous crops

Leguminous crop	Methods	Effect	References
1. Root nodulation and biological nitrogen fixation			
Garden pea	CP	Enhances nodulation and biological nitrogen fixation	(11)
Soybean	Non thermal plasma	Increase nitrogenase activity in nodules; Increase nodule leghemoglobin content	(37)
2. Removal of seed contamination			
Phaseolus vulgaris	low-pressure oxygen plasma	disinfection and stimulation of radicle growth	(39)
Soybean	dielectric barrier discharge plasma	Plasma-treated seeds outperformed fungicide-treated seeds in growth and agronomic traits.	(40)
Pea	CAPP	Decontamination and germination of pea seeds	(41)
Mung bean	PTW	Microbial decontamination	(42)
Mung bean	dielectric coplanar surface barrier discharge (DCSBD)	Reduced the total microbial population in sprouts	(43)
Mung bean	PAW	Reduction of Log_{10} 1.76 cfu/g E. *coli* O157 on mung bean seeds	(46)
3. Dormancy breaking			
Mung bean	Non-thermal atmospheric pressure plasma	NO-induced upregulation of the natural growth hormone gibberellic acid	(48)
Desmanthus virgatus	low-pressure plasma	Breaks seed dormancy	(49)
Black locust	Non thermal Plasma	Modified the surface and enhancing germination.	(50)
Leucaena leucocephala	CAP	Partially overcome the dormancy barrier	(51)
4. Seed germination			
Mung bean	CP	Increased the seeds coat conductivity, hydrolytic enzymes activity like amylase, protease and phytase	(54)
Pea	CAPP	Stimulating effect on germination, growth and development of seedlings.	(55)
Guar bean	ACP	Enhanced seed germination	(56)
Phaseolus vulgaris **Common bean**	CAPP	Cold atmospheric pressure plasma	(57)
Pea	low-temperature plasma	LTP modified seed structure, accelerating germination and plant signaling hormones.	(58)
Soybean	CP	Germination and vigor indices significantly increased	(60)
5. Drought Stress			
licorice seeds (*Glycyrrhiza*)	surface dielectric barrier discharge (SDBD)	Allieviated drought stress-induced damage	(64)
Alfalafa	CP	Enhanced adaptability of alfalfa seeds in different drought environments	(65)
Zucchini	CAP	Increased drought resistance and germination of seedlings after plasma	(66)
6. Reduction in pest and pesticide residues			
Soybean	CP	Reduced chlorpyrifos residues	(68)
Chickpea	CP	Controlled *Callosobruchus chinensis*	(69)
Cowpea	ACP	Had a considerable impact on the mortality of a range of insect (Cowpea weevil) life stages	(70)

alternative methods to mitigate pesticide residues and insect infestations in legumes while preserving seed quality. A study evaluating ozone and CP treatments for chlorpyrifos residue reduction in soybean seeds found that ozone lowered pesticide levels by 50 % after 30 min, whereas CP achieved the same reduction in just 6 minutes. However, CP caused minor moisture loss and seed coat damage while increasing water absorption. Despite higher pesticide concentrations slowing degradation, CP remained more effective than ozone with minimal seed quality impact (68). CP has also demonstrated effectiveness in pest control, particularly in chickpeas. Plasma-treated chickpeas exhibited extended protection against pulse beetle infestations during storage, especially when stored in airtight pouches. This pesticide-free approach not only safeguards grains but may also enhance cooking efficiency and shelf life (69). Additionally, CP at 70 kV effectively eliminated *Callosobruchus maculatus*, achieving over 90 % mortality in eggs and larvae and 95 % in adults within four days post-treatment. Using a gas mixture of 65 % oxygen, 30 % carbon dioxide and 5 % nitrogen, this method presents a safer and efficient alternative to chemical fumigation (70). These advancements highlight the potential of non-chemical technologies for pesticide residue removal and pest control in legumes, ensuring safer storage, improved seed quality and reduced environmental impact while supporting sustainable agricultural practices.

Plasma-activated water (PAW) for irrigation/seed treatment

Plasma discharge, whether above or within water, has proven effective in deactivating a wide variety of microorganisms. Research indicates that the physicochemical properties of PAW, especially nitrogen species like nitrates, are crucial for its antimicrobial effects and its ability to promote plant growth by providing essential nutrients. PAW also disrupts hormones linked to seed dormancy, encouraging growth. Overall, PAW functions similarly to CP, aiding in disinfection, decontamination and improving seed germination and plant growth (2). In *Erythrina velutina* (mulungu), PAW treatment enhanced germination by modifying the micropyle and hilum, improving water absorption (71). The combination of ultrasound and PAW further optimized germination, with ultrasound enhancing water uptake while PAW stimulated metabolic activity (72). In *Vigna mungo*, PAW-induced H_2O_2 accumulation, regulated by catalase activity, promoted germination and seedling growth, with gene expression and molecular docking confirming its role in stress adaptation (73). Similarly, nitrogen PAW (NPAW) improved *Vigna radiata* seedling vitality and hypocotyl elongation, with transcriptome analysis identifying 179 upregulated genes linked to stress response (74). In soybean, PAW accelerated germination, increased biomass accumulation and, when combined with ZnO nanoparticles, reduced lead (Pb) uptake by five fold (75). It also boosted seed production in crops, with SEM analysis revealing plasma-induced surface modifications (76). Additionally, PAW enhanced shoot length, vigor index and chlorophyll a content in soybean, though chlorophyll b and carotenoids declined (77). These findings highlight PAW as a transformative agricultural innovation, offering a sustainable approach to enhancing crop performance, stress tolerance and environmental safety. As research continues to uncover its mechanistic foundations, PAW stands as a key advancement in sustainable crop production and food security.

Combining cold plasma with other technologies

Cold plasma and nanotechnology

CP seed priming is hypothesized to induce a cascade of biological, biochemical and molecular responses. By altering the seed coat, this technique generates free radicals, leading to a substantial increase in yield. The involvement of RONS is presumed to be pivotal in this priming mechanism (78). The effects of CP priming and SiO_2 nanoparticles on *Astragalus fridae* growth were explored, showing enhanced growth, enzyme activities and modified stem/ root diameters, with potential applications in plant science and *in vitro* systems (79). The use of nanochitosan and plasma-activated water on vetch beans improved germination, reduced salt stress and minimized microbial contamination. This combination boosted yield, protein content and microbiological quality, even in high salinity, making the sprouts viable for both fresh and dried consumption (80). Seed priming with CP or its combination with silicon nanoparticles mitigates sodium ion uptake and translocation within plant tissues while promoting potassium (K^+) accumulation, thereby alleviating oxidative damage induced by salt stress (81).

Cold plasma and magnetic field

Magnetic field (MF) exposure induces physiological modifications in plants, promoting enhanced growth and yield under both optimal and challenging conditions. By stimulating energy production and its efficient distribution to cellular biomolecules, MF application accelerates seed germination, as well as vegetative and reproductive development in plants (82). Numerous studies have demonstrated that pre-sowing seed treatments involving low-temperature plasma and electromagnetic fields (EMF) can enhance germination, early growth and subsequent plant development (reviewed in). The effects of CP and electromagnetic field treatments on red clover seeds were analyzed, revealing enhanced germination, altered phytohormones and improved root growth and nodulation. Flavonoid shifts in root exudates strengthened communication with nitrogen-fixing rhizobacteria, fostering beneficial plant-microbe interactions (83). CP and electromagnetic field presowing treatment improved red clover germination (4 % - 20 %), growth (up to 49 %) and protein yield (70 %). A 5-min CP treatment altered isoflavone composition, increasing the biochanin A/formononetin ratio before flowering but reducing it at flowering (84). The effects of CP and EMF treatments on red clover seeds were evaluated. The treatments improved germination, particularly in yellow seeds and boosted root nodules, especially in dark purple seeds (85).

Cold plasma and machine learning

Machine learning (ML) plays a significant role in modeling and simulating CP behavior, providing insights into its chemical and physical interactions with different surfaces. It aids in developing predictive models by using surrogate approaches to approximate physics-based predictions while also analyzing experimental data to identify plasma surface interaction patterns. This is particularly valuable when detailed theoretical models are unavailable. Various computational techniques, such as fluid models, particle models and hybrid fluid-particle models, are commonly used to simulate CP dynamics and enhance its applications (78). ML can effectively monitor changes in plasma properties, providing valuable insights for analyzing and reducing inconsistencies in plasma behavior. Advanced diagnostic methods allow for real-time detection of operational instabilities and gradual shifts in plasma characteristics. Continuous monitoring is essential for improving the stability of CP sources, enhancing reliability and minimizing variability in performance (86).

Conclusion

The drive for sustainable agriculture has spurred research into boosting plant productivity with less nitrogen fertilizer. CP seed treatments show great promise in enhancing plant growth, development and SNF in legumes. They promote root elongation, lateral root formation and biomass accumulation while modifying flavonoid exudation, potentially influencing plant-rhizobia interactions and further improving overall productivity. Modifying gas composition, flow rate, power, frequency and treatment duration influences CP's active constituents. Despite varied approaches, studies consistently report positive effects on legumes. For commercial viability, extensive validation under field conditions is needed, along with regulatory, health, economic and ecological assessments to ensure widespread adoption (87). Recent advancements integrating CP with nanotechnology, magnetic field exposure and machine learning are further revolutionizing its applications. Nanotechnology enables targeted nutrient delivery, optimizing plant metabolism, while magnetic field treatments enhance water absorption and metabolic activity. ML algorithms refine CP treatment protocols, ensuring precision and efficiency tailored to specific crop and environmental conditions. As research continues to advance, CP stands poised to become a cornerstone of climate-resilient and high-efficiency agriculture, reducing dependence on chemical inputs while fostering sustainable food production. Further interdisciplinary exploration will unlock new frontiers, cementing cold plasma's role in next-generation legume agronomy.

Acknowledgements

The authors would like to express their gratitude to Tamil Nadu Agricultural University for providing the necessary facilities and support for writing this review article. Finally, we appreciate the constructive feedback from the reviewers and editors, which helped to improve the quality of this manuscript.

Authors' contributions

RJ and A did literature search, manuscript writing and original draft preparation. JR and VS did critical analysis of literature, data interpretation and manuscript editing. SR and PG did review structuring, visualization and manuscript revision. MV did supervision, final review and approval of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Author's do not have any conflict of interest to declare.

Ethical issues: None

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