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Advancing seed quality through cold plasma technology: A sustainable approach for agricultural enhancement

M Biruntha[1], C Menaka[2*], A Yuvaraja[3], C Vanitha[4] & R Ramjegathesh[3]

[1]Department of Seed Science and Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[2]Indian Council of Agricultural Research-Krishi Vigyan Kendra, Tamil Nadu Agricultural University, Pudukkottai 622 303, India

[3]National Pulses Research Centre, Tamil Nadu Agricultural University, Pudukkottai 622 303, India

[4]Department of Seed Science and Technology, Seed Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, India

*Email: menaka.c@tnau.ac.in

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Abstract

Seeds are exposed to various physical and biological stress during germination. Water uptake plays a major role in germination as it determines the permeability of the seed coat. To enhance seed coat permeability during germination, various technologies have been adopted. Among them, cold plasma technology has emerged as a developing and environmentally sustainable physical seed treatment method. Cold plasma, a non-destructive method using partially ionized gas with reactive species, offers benefits such as seed disinfection, pathogen elimination, enhanced seed metabolism and improved germination. However, challenges related to adaptability, cost-effectiveness and standardization remains. Ongoing research is needed to optimize its use for various seed types and conditions. Addressing these challenges requires continuous research and development to optimize cold plasma treatment for various seed types and environmental conditions. This paper provides the underlying mechanisms of cold plasma effects on seeds, highlighting its potential to expertise seed treatment practices for sustainable agriculture. Thus, cold plasma technology points as a promising avenue for enhancing seed quality, disease management and crop productivity in agriculture. By standardizing various treatments with cold plasma, it is possible to meet the challenges of the 21st century thereby minimizing the environmental impact and pave the way for sustainable agriculture, while making it efficient for commercial scale.

Keywords

cold plasma technology; germination; metabolism; seed disinfection

Introduction

The agricultural sector is facing numerous challenges like global population growth, environmental degradation land availability and climate change. Notably, climate change has led to substantial declines in crop yields, posing a severe threat to global food security (1). Based on a 2021 assessment by the United Nations Food and Agriculture Organization (FAO), global grain production stands at 2.216 billion tons. However, the demand for grains is estimated to be around 2.25 billion tons, resulting in approximately 9 million people worldwide facing food insecurity (2). A range of strategies and technologies have been introduced to address the evolving challenges in agriculture, including precision farming, sustainable irrigation systems and advanced biotechnology. Among these, efficient land use and management, adjustments in food demand patterns and efforts to minimize food waste and losses are frequently recommended as adaptation measures (3).

Plasma, recognized as the fourth state of matter in physics and chemistry, presents a promising approach for stimulating seed germination without leaving any residual effects. This method involves ionizing gas, which requires an energy input and results in a mixture of reactive species, including electrons, ions, excited species, radicals, UV radiation and electromagnetic fields (4, 5). Plasma treatment can initiate physiological and biochemical processes within seeds, leading to beneficial physical alterations that enhance germination (6).

Electrons exhibit higher energy levels in cold atmospheric plasmas (CAPs), while ions remain at lower energy levels at room temperature. This temperature distribution ensures that cold atmospheric plasma does not cause any thermal damage to seeds. Due to the presence of reactive species, plasmas find extensive use across various applications like surface treatment (7), sterilization (8), food packaging (9), medical treatments (10) and agricultural practices (11).

A recent study expressed the effects of plasma-activated water (PAW) treatment on seed germination and the growth of mung bean sprouts, demonstrating that PAW positively influenced seed germination and subsequent growth (12). The physical components of plasma, including heat, ultraviolet light and electromagnetic fields, directly interact with the seed coat during plasma treatment and potentially influence seed germination, growth and development. Further, the impact of these physical elements of plasma on seed germination and growth has been addressed (13).

In 2017, a study on the effects of plasma-activated water (PAW) on seed germination and plant growth in radishes, tomatoes and sweet peppers was conducted revealing that the non-thermal plasma generates reactive oxygen species (ROS) and nitrogen species (RNS), such as NO^{3-}, H_2O_2, O_2 and O_3, within the water (14). This acidified water can serve as a fertilizer due to its ability to enhance the rate of seed germination up to 80 %. Furthermore, they found that PAW positively influences the germination of dried seeds and seedling growth, while it negatively affects the germination of wet seeds. In recent years, there has been growing interest in exploring the effects of cold plasma on various seeds, including wheat (15, 16), maize (6), radish (17, 18), oilseed rape (19), tomato (20, 21), cotton (22) and rice (23).

The results of these studies have consistently shown that plasma treatment significantly enhances both seed germination and seedling growth. This improvement is attributed to increased water uptake by the seeds during imbibition, which facilitates better nutrient absorption, consequently leading to enhanced shoot length, root length, shoot dry weight and root dry weight in seedlings.

Cold plasma technology -an outlook

Plasma, the fourth state of matter, is characterized by a higher energy state than solids, liquids, or gases. It is made up of various components, including electrons, positively and negatively charged ions, free radicals, gas molecules, excited and ground state atoms, excited molecular, ionic and radical species. The visible light and ultraviolet photons of electromagnetic radiation quanta are essential components of plasma (24). In the agricultural and food sectors, cold plasma technology is a quick and non-invasive treatment that can either replace or supplement a number of production stages, such as reduced bacterial levels during harvest (25) and pesticide degradation (26, 27). In the past, low pressure was used to create plasma discharges by reducing the density of gas molecules (the number of molecules per unit volume). This made ionization possible at lower electric potential differences. Nowadays, cold plasma can be maintained in ambient air itself. When compared to the low-pressure plasma, the atmospheric pressure plasma generation system is easier to use and more significant (28).

The most important properties to consider are the energy and electrical density of plasma. Based on the microscopic characteristics, many natural or artificial plasma types can be classified into two groups: hot and cold plasmas. Artificial plasmas, or Cold plasmas (CP), are created using low-frequency (0.02-0.4 MHz), microwave (0.5-few GHz) or radio frequency (RF), decrease of flux infiltration (<500 MHz) discharge at relatively low pressure (10-2–10 Torr) (29). Food goods can be preserved with cold plasma treatment by either preserving the bioactive ingredients or shielding food from microbes. The bacterial cell is killed by the action of cold plasma, which is hazardous to the microbes. There is no negative impact associated with the ionized gas generated from the plasma (30). In particular, air plasmas contain reactive nitrogen species (RNS) like nitric oxide (NO), peroxynitrite and nitrogen dioxide radical (NO_2), as well as reactive oxygen species (ROS) including superoxide (O_2), hydrogen peroxide (H_2O_2), hydroxyl radical (OH), singlet oxygen ($^1O_2$) and ozone (O_3) (31). Along with lowering reactive oxygen and nitrogen species (ROS and RNS), the plasma created modifies the solutions chemical and physical characteristics, including pH, electrical conductivity and oxidation-reduction potential (32).

Electric fields can ionize gases, including argon, oxygen, nitrogen helium and/or air, producing electrons, ions, UV, heat radiation and reactive species. Cold plasma has shown beneficial effects on plant growth, yield and root development in soybean (33) and has been found to promote the growth of wheat and oat (34). Since all the components of plasmas may be found in nature and quickly recombine. Plasma treatment may increase seed survival without leaving harmful residues. Additionally, the components in plasma only penetrate around 10 nm deep, which restricts them to surface functionalization (35). Therefore, in recent decades, cold plasma (low pressure) technology has been successfully applied to increase the germination and growth of a variety of crops (36). However, more research is necessary to fully understand the impact of CP-treated food on human consumption due to the lack of evidence that is already available (37).

Types of cold plasma treatments

There are different types of plasma treatments that has been used widely. Several methods like corona discharge, glow discharge, dielectric-barrier discharge and atmospheric pressure plasma are most used. A summary is presented in Fig. 1.

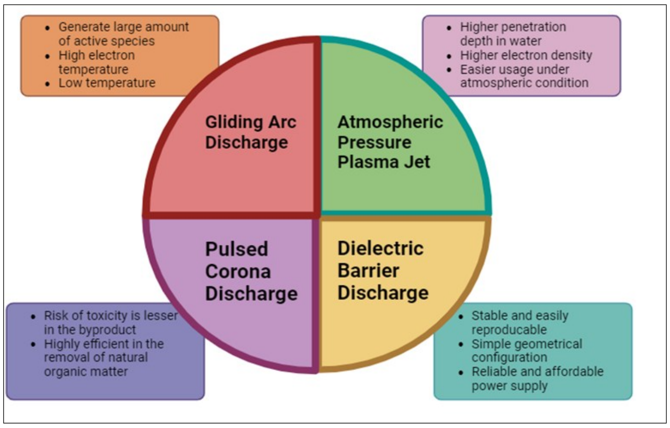

Fig. 1. Different types of cold plasma treatment.

Atmospheric Pressure Plasma

Atmospheric pressure plasma (CAPP) requires no vacuum apparatus and is less expensive. To enhance seed germination, it is crucial to make seeds more wettable by increasing the hydrophilicity of the seed coat surface. This improvement helps boost water absorption, which supports the germination process (38). The activity of succinate dehydrogenase, an enzyme involved in the Krebs cycle, was dramatically increased in seeds treated with lower levels of cold atmospheric pressure plasma produced in ambient air and oxygen. This demonstrated the transition of the metabolism of germinating seeds from anoxygenic to oxygenic (39).

When seeds are treated with cold atmospheric pressure, several aspects of their development are affected. These include the percentage of seeds that germinate, their morphology (such as shoot height, root length and surface area), gene expression and biochemical reactions. Biochemical changes may involve modifications in hormone levels, antioxidant levels, amino acid composition, total soluble sugar content and chlorophyll content. Following plasma treatment, the modifications were applied to yield-related metrics (seedling fresh and dry weight) and water absorption capacity (40).

Dielectric-Barrier Discharge

Two parallel metal electrodes coated with dielectric materials like quartz, polymer, or plastic make up dielectric-barrier discharge (DBD). These substances primary purpose is to aid in controlling the output plasma's uniformity (41). Source gases can create excited atoms, molecules, ions and active radicals through electron impact ionization and excitation (42) as show in Fig. 2.

Moderate-intensity DBD plasma positively significantly enhanced the development of seedlings and the germination of wheat seeds. After 4 minutes of air plasma, nitrogen plasma and argon plasma treatments, germination potential increased by 24.0, 28.0 and 35.5 % respectively. Shoot and root length also increased. No enhancement was seen after

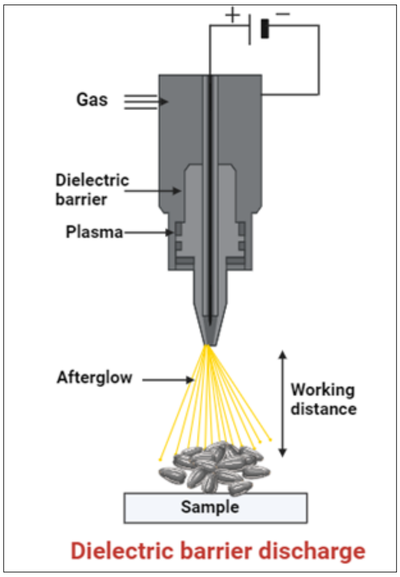

Fig. 2. Dielectric barrier discharge method of cold plasma treatment.

the oxygen plasma treatment (43).

Black gram with a waxy seed coat became smoother and thinner, when it is treated with 400 torr dielectric barrier discharge air plasma treatments. Due to the thinner seed coat, the widening of the micropyle and enhanced adsorption, diffusion and trapping of reactive nitrogen species (RNS), the imbibition rate increased with longer CP treatment (44).

Radio-Frequency Low-Pressure Plasma and Corona Plasma

The complex stressor known as radio-frequency low-pressure plasma, or cold plasma, can affect biological systems due to its various components, which include charged particles, vacuum, UV radiation, high frequency electromagnetic radiation and subsequently generated reactive chemical species (45).

A high-voltage electrical discharge between two electrodes, such as a thin wire plate or a sharp pin plate, with differing radii of curvature, produces corona plasma. The voltage required to start the discharge is lowered by the powerful, localized electric fields produced by these sharp edges. As a result, the discharge across the low potential or ground electrode surface is fixed (46).

A non-uniform electric field has the potential to cause a corona discharge. Corona discharge field biological mutagenesis technology is a physical mutagenesis method that is environmentally friendly, uses straightforward equipment and clearly manifests its biological effect (47). Small seeds can be treated using a corona discharge reactor that has been modified with a horn-shaped nozzle. This reactor's ROS-rich plasma environment makes oxygen radicals to be incorporated at the seed coat, which significantly increases surface wettability. The number of seeds that can be inserted between the electrodes was shown to be a crucial parameter for process homogeneity and reproducibility when using the direct treatment strategy (48).

Application of cold plasma in agricultural sector

Agriculture is also paying more attention to plasma treatment since agricultural yields have been decreased due to climate change in quantity and quality of crop (49). Fruits and vegetables grown for food are frequently contaminated throughout the harvest and postharvest (transport, storage, cleaning, packing and food processing) stages due to contact with dust, insects, animal urine and feces, people and equipment (50). In addition, pathogen resistance (many pests have become resistant to pesticides, leading to the creation of new diseases) and environmental pollution are making chemical-based techniques less popular (51).

In agriculture, bacterial (such as *Erwinia carotovora*, *Clavibacter michiganensis* and *Pectobacterium carotovorum*) and fungal (such as Alternaria, *Aspergillus, Botrytis*, Colletotrichum, Fusarium and Penicillium) pathogens are the main targets of plasma inactivation procedures (52). Research employing cold plasma validates a number of beneficial impacts on crops, including overcoming dormancy (53), enhancing germination (54), maximization of enzyme activity (55), encouraging the growth of seedlings (53). Laboratory experiments show that direct and indirect treatments on plants, such as wheat, corn, chili pepper, lentils and tomato, can alter germination rate, plant morphology, gene expression and biochemical processes, leading to improved growth and yield (56).

These treatments can be used for maintaining agricultural product freshness and quality postharvest. They highlighted the importance of removing ethylene during storage and transportation, which can induce undesirable reactions and increase disease vulnerability, through atomic oxygen oxidation (57). Despite the aforementioned benefits, a different research team found that because of prolonged treatment it might seriously harm the seed surface, sprout growth is not directly correlated with plasma energy (53). Thus, more research to maximize the benefits of Atmospheric pressure plasmas is still necessary to avoid oxidative damage and seed deterioration (44) (Fig. 3).

Different approaches of cold plasma treatment in seed quality

***Cold plasma priming*:** Seed priming is a pre-sowing process which speed up the germination process (58). It enhances seed vigour, shortens the germination period and reduces seedling mortality. Traditional priming techniques include hydropriming, halopriming, osmopriming, biological priming, chemical priming and hormonal priming (59). Cold plasma seed priming, a newer technique, differs from these methods by physically modifying the seed surface rather than relying on water or chemical absorption. It increases seed coat permeability, enhances water uptake and stimulates biochemical pathways that regulate growth and stress resistance. Unlike conventional priming, which mainly activates metabolic processes through hydration, cold plasma alters gene expression, boosts antioxidant activity and improves nutrient absorption, leading to superior germination efficiency and seedling growth. When cumin seeds were primed for five minutes, their roots grew noticeably longer than those of control seedlings; however, there was no difference in the root length of control seedlings and seeds that were seed primed for ten minutes (60). Cold plasma treatment and salicylic acid priming can enhance rice growth and nutrient uptake under salinity stress by decreasing ROS production and increasing antioxidant enzyme activities. These treatments also regulate enzyme-related secondary metabolism, which involves biochemical pathways that produce compounds essential for plant stress tolerance and growth. For example, secondary metabolism includes the production of antioxidants like flavonoids and phenolics, which help plants cope with environmental stress. Additionally, key enzymes such as peroxidases and superoxide dismutases play a role in scavenging harmful reactive oxygen species (ROS), protecting cells from oxidative damage. By enhancing these metabolic processes, cold plasma treatment can improve root and leaf cell structure, making rice more resilient to high salinity soils (61).

Additional research shown that CP seed priming improved the physiological and biochemical traits of seeds during the germination stages, such as the levels of proteins, carbohydrates and antioxidants. Plants produce salicylic acid and jasmonic acid in response to hydrogen peroxide. As a result of CP primed seedlings accumulating hydrogen peroxide in the form of salicylic and jasmonic acid, levels of these compounds are induced (21).

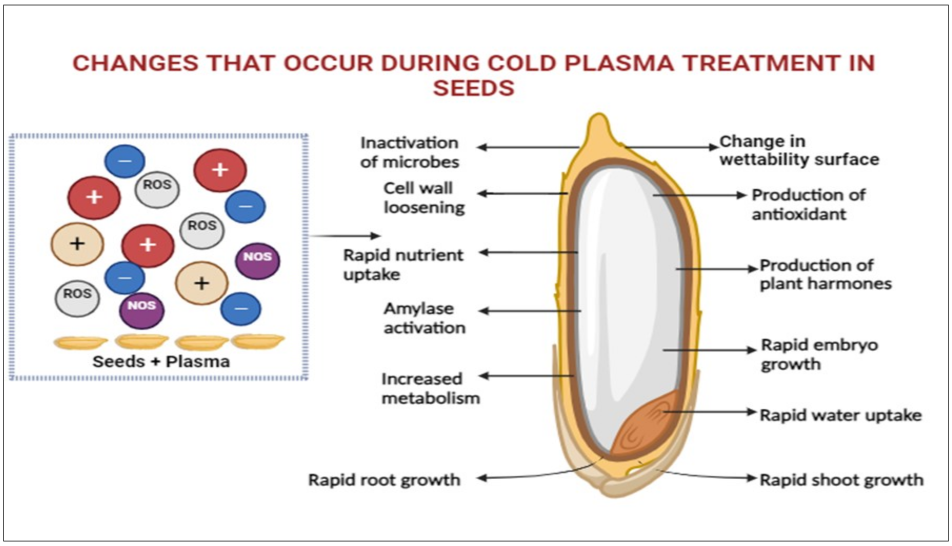

Fig. 3. The changes that occur during cold plasma treatment along with seeds.

The interplay of morphological, physiological, biochemical, molecular, genetic and hormonal elements in tomato seedlings to show how CP seed priming treatments modify cold stress tolerance at the molecular levels they practiced a complex physical and chemical interactions involving neutral gas, ionized gas, ROS, RNS molecules, electrons and positively charged particles. A development and stimulation was observed in the embryo of tomato seeds exposed to CP therapy (62). By using low-pressure CP in the air, it can overcome seed dormancy in *S. leriifolia* plants. The optimal treatment, 100 W of CP for 240 sec, increased seed germination by over twice compared to the control. Further research is recommended for accounting the various effects of cold plasma technology in seedling growth (63).

Integrated approach of cold plasma seed priming with nanoparticles

Regarding seedling growth and germination, plant species from all over the world have profited from nano-priming by using a variety of nanomaterials, such as silicon, zinc oxide, titanium dioxide, silver nanoparticles and carbon-based nanomaterials, which enhance germination, seedling growth, stress tolerance and pathogen resistance (64). At molecular level, cold plasma and nanoparticles function as a seed priming treatment. The strengthening of antioxidant enzyme systems and the stimulation of defence response in seed treated with nanoscale particles and cold plasma improve physiological processes and aid in pathogen inactivation (65). Treating seeds with cold plasma reduced the toxicity risk linked to high levels of selenium nanoparticles, demonstrating its potential for enriching the nutritional value of seeds, particularly those used in seed-based foods (66).

Zinc oxide (ZnO) nano particle and plasma treatments influenced peroxidase activity in the growth media, triggering a defence response. Furthermore, the treatments led to increased activity of phenylalanine ammonia-lyase (PAL) and soluble phenols in the roots and leaves. Cold plasma treatment also counteracted the inhibitory effects of ZnO on xylem differentiation. In the pot experiment, soaking the seeds before plasma treatment was identified as the most effective method for enhancing plant growth (67).

Cold plasma and low doses of Si supplemented rooting culture media showed promise in enhancing plant growth, physiology and defence mechanisms by altering cellular metabolism, stimulating growth rates, influencing tissue differentiation and triggering antioxidant enzyme activity. This study contributes to understanding plant-plasma interactions and could advance plant science (68).

Plasma priming with selenium nanoparticles *Cichorium intybus* at low doses can promote plant growth, early seedling performance and can associate with long-term responses in plants. Cold plasma seed priming mediates modification in flowering processes (69). The immediate and long-term benefits of applying carbon nano tube and plasma separately or in combination to bitter melon seedlings. The potential benefits of seed priming with plasma and multi walled carbon nano tubes in *Momordica charantia* was early growth, tissue differentiation patterns, architecture, reproductive efficiency and putative contributory pathways (70). Therefore, employing plasma treatment as a new priming method could enhance plant protection measures (66).

Impact of cold plasma treatment on physiological parameters of seed

***Effect of cold plasma treatment on seed germination*:** Crops such as mung bean (53), rice (71), wheat (72) was exposed to atmospheric pressure cold plasma treatments which enhanced the germination of the seeds. Several research also mention the impact of plasma on the surface, which increases surface hydrophilicity and encourages seedling growth (53). When seeds are exposed to plasma discharge, organic pollutants are eliminated and surface alterations such oxidation, erosion, corrugation and hydrophilization are caused (21). These changes improve water uptake during germination by altering the seed coat's hydrophilicity, roughness and water contact angle (44).

Roughness on seed surfaces affects wetting and seed imbibition. Increased roughness enhances water-drawing characteristics, while water penetration improves wetness if δ is less than 90°. Water does not enter if δ is greater than 90°, reducing wetness. Bush bean (*Phaseolus vulgaris*) seeds subjected to longer plasma treatment times exhibit smaller water droplet contact angles and larger hydrophilic pore diameters, facilitating improved water uptake(73). Plasma activated water is treated with several seeds, from that mustard and mung bean seeds has been germinated in 2 days where as wheat, dianthus, lettuce, radish and sticky bean germinated in 5 days. But tomato seeds took almost 10 days to sprout (54). The same outcome using peppers, tomatoes and radishes as models; a particular circumstance may promote radish growth but inhibit tomato development (14).

Interestingly, it was found that only the concentration of hydrogen peroxide increases in the seeds, roots and leaves of black gram plants, despite the fact that atmospheric cold plasma may enhance the level of signal molecules like nitric oxide and hydrogen peroxide (44). Even a minute of CAPP treatment significantly increased seedling growth in *Arabidopsis thaliana*. The plasma treatment accelerated seedling abscisic acid (ABA) accumulations, which regulate the concentration of calcium and RONS, which are easily transported through the cell membrane. RONS serve as nutrients and signalling molecules in the growth process (74). A trial on paddy field with both direct and indirect treatments with plasma-activated Ringer's lactate solution was conducted. It showed that plasma treatment improved plant growth, grain yield and quality, with direct exposure experiments increased grain yield up to 15 % (75).

***Effect of cold plasma treatment on root growth*:** During embryogenesis, root growth begins. All root layers constantly generate from stem cells at the tip, under the guidance of cytokinin-induced differentiation and a continuous auxin influx (76). A number of variables affect root growth and development, including the availability of carbohydrates from photosynthesis or reserves, plant hormone signalling and soil nutrient uptake (77). Five-week-old red clover seedlings treated with five and seven minutes of continuous plasma treatment showed increases in root length of 27 % and 37 % and increases in the number of lateral roots of 82 % and 77 %, respectively. Interestingly, CP therapy had a greater influence on root branching than on root length (78).

Cold plasma may be employed in future for economically significant plants vegetative propagation (79). When cumin seeds were pre-treated with CP for five minutes, the root surface area and volume of the seedlings increased dramatically by 23.5 % and 37.8 %, respectively, in comparison to the control group. However, the volume and surface area of the seedling roots were unaffected significantly by the 10 min CP pre-treatment (60). Seedlings with yellow seed coats were treated for five- and seven-min in cold plasma showed 39 % and 42 % increase in root length, respectively, in the red clover experiment based on seed coat colour dependency. On the other hand, dark purple seeds treated with CP for 5 min showed a 31 % increase in root length (80).

The zoysia grass stolon cuttings root development and rooting percentage was both significantly increased by a 300 W cold plasma therapy. The improved permeability and water uptake of the cuttings is due to the rise in root development and rooting percentage (79). There is increase in weight and root length of red clover seedlings with 2.5 and 25 % fold increases, respectively, during the first year of vegetation's one to two trifoliate leaf stage (81). When compared to untreated plants, mature soybean plants that were 40 days old showed improvements in root length and root dry weight following dielectric barrier discharge plasma therapy (82).

***Effect of cold plasma treatment on shoot growth*:** Several studies have shown that plants cultivated from CP-treated seeds exhibit notable increases in shoot length, as well as fresh and dry shoot weight. In red clover plants, CP and electromagnetic field treatments significantly enhanced shoot growth parameters. Field studies conducted over the first and second years of vegetation revealed sustained improvements in biomass production, plant density and overall vigour (80). In the first year, treated plants exhibited faster germination, increased shoot length and improved root development, leading to stronger early-stage growth. By the second year, these benefits translated into higher forage yield and resilience to environmental stress, demonstrating the long-term advantages of CP seed treatment in real-world agricultural conditions (81).

The DBD system's 3 and 6 min exposures as well as the PER system's 3 min exposure showed the greatest gains in the phenotypic traits of legume-lentil or pea (i.e., nodule number, dry weight, root dry weight, length, volume and surface area and shoot dry weight) (28). Regarding *Oryza sativa* the maximum dry and fresh weight of root and shoot was considerably recorded when salicylic acid priming and plasma therapy were combined (61).

***Effect of cold plasma treatment on seedling vigour*:** In sweet basil, seed germination and seedling vigour are significantly increased by a cold plasma therapy. It is the result of increased protein and sugar content that dissolves, increased water absorption and increased use of seed reserves. The germination of sweet basil seeds is a crucial component of seed production technology and storage which responds favourably to cold plasma treatments (83).

Under both normal and salinity stress circumstances, paddy seeds are treated with 2 mM salicylic acid (SA) and 10 kV of plasma which produced the highest seedling vigour index in the cultivars of Zhu Liang You 06 (ZY) and Qian You No. 1 (QY) (61). When compared to untreated barley seedlings, an ideal treatment with 80 W dielectric barrier discharge plasma greatly improved the germination capabilities of the seeds, resulting in a better germination percentage and vigour index. It also improved the water absorbing capacity of the seeds (84).

Plasma treatments of 30–60 sec can greatly enhance the wheat seed germination characteristics as well as the seedling growth metrics. The most effective method was to treat the seeds indirectly with plasma for 60 sec and then allow the seeds to come into contact for 24 hr after treatment. This increased the germination rate of wheat by 14.7 % when compared to the untreated controls. Germination index and seedling vigour was also increased (85). Cold plasma treated okra seeds registered maximum germination, vigour index than the untreated seeds and promotes the water uptake (86). CP treatment optimistically influenced the physical and chemical properties of the seed and also induced growth and yield attributes in field conditions (87).

***Effect of cold plasma treatment against pathogen infestation*:** High effectiveness of low-pressure radio frequency plasma promotes seed germination and early growth as well as reducing fungal infection. This improvement enhanced the sowing value, viability, health and crop yield of several significant agricultural crops, including winter wheat, maize and narrow-leaved lupine (88). Cold plasma therapy effectively reduces the survival rates of bacteria, fungi and phytopathogens on the surface of ginseng seeds. Low-temperature plasma has fungicidal and bactericidal properties that improve germination and root growth in ginseng seeds. It is especially useful in managing ginseng root rot (89).

The potential to inactivate *C. gloeosporioides* exists in the emulated plasma activated hydrogen peroxide solution (EPAS-H). The results show that the fungal pathogen was killed by the EPAS-5 % hydrogen peroxide treatment, which also broke down the fungal cell wall, enhancing pepper seed germination, seedling germination index, growth rate and seedling biomass (90).

In addition to lowering or suppressing fungal diseases of plants during the phase of active vegetative growth (in the case of lupines, up to the flowering stage), pre-sowing plasma treatment reduced fungal contamination of seeds and improved plant yield under natural field conditions (88). The shockwave produced in the water during arc discharge removes spores from the seed surface. The surface dielectric-barrier discharge plasma under low pressure was found to be containing hydrogen peroxide for both disease development and disinfection. Therefore, during aerobic storage, this technique could be utilized to keep seeds free of fungus (23) (Fig. 4).

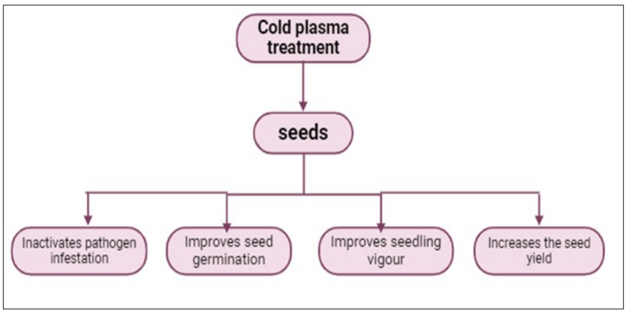

Fig. 4. Effect of cold plasma treatment on seeds.

Performa of different crops

Various studies on seeds with distinct objectives were made by many researchers in cold plasma technology. Each of them had found out different results when treating the seeds with various treatments in extended time periods. It has been noticed that this technology is beneficial in improving seedling germination, vigour, increases the root length, shoot length and nitrogen fixation. Other than agriculture all these techniques play a major role in food processing, waste management, medicine etc. An overview of cold plasma treated seeds and their effects on the seeds of various crops are given in the table. All these studies emphasized that this technology is empowered with maximum positive results (Table 1).

Conclusion

Cold plasma technology is a promising seed treatment method that enhances germination, seedling vigour and overall crop yield while ensuring microbial decontamination without compromising seed viability. Unlike conventional methods that can damage seeds, cold plasma operates at low temperatures, minimizing harm and reducing the need for chemical treatments, making it an environmentally friendly alternative. Though initial investment costs are higher, its long-term benefits outweigh conventional approaches by promoting healthier crops and sustainable agriculture. Future research should focus on optimizing treatment parameters, understanding molecular mechanisms and ensuring the safety and reproducibility of cold plasma applications. Addressing potential genotoxicity and refining large-scale implementation will be crucial for integrating this technology into standard agricultural practices. With continued advancements, cold plasma seed priming could revolutionize modern farming, improving productivity and sustainability.

Table 1. Impact of cold plasma treatment on various crops

No	Seed	Exposing time limits	Pressure used	Gas used	Source of plasma treatment	Frequency range/ voltage	Results obtained	Reference
1.	Rice (*Oryza sativa*)	30 min	Low and atmospheric pressure	-	Arc discharge & dielectric-barrier discharge	12 Hz	Enhanced disease resistance and seed germination	(23)
2.	Wheat (*Triticum aestivum*)	6 hr (after plasma)	Atmospheric pressure	Argon	Dielectric-barrier discharge	80 W	Enhanced growth and resistance to salt in wheat	(67)
3.	Maize (*Zea mays*), wheat (*Triticum aestivum*)	5–90 s	Low pressure	Helium	Corona discharge& glow radio frequency	13.56 MHz, 50 -1000 W	Enhanced germination	(91)
4.	Barely (*Hordeum vulgare*)	40s	Atmospheric pressure	Nitrogen and air	Dielectric-barrier discharge	400 W	Increased plant growth and seed germination	(92)
5.	Soyabean (*Glycine max*)	60 to 180s	Atmospheric pressure	Nitrogen, oxygen& argon	Needle to plane dielectric-barrier discharge	25 kV, 50 Hz	Increased yield and germination of seeds	(93)
6.	Pea (*Pisum sativum*)	1-10 mins	Atmospheric pressure	Air	Dielectric-barrier discharge	15 W	1-10 min enhanced seed growth	(94)
7.	Mung bean (*Vigna radiata*)	3 min	Atmospheric pressure	Nitrogen, oxygen &argon	Plasma jet	0-20 kV, 9.0 kHz	Enhancing the growth of seedlings and seed germination	(95)
8.	Black gram (*Vigna mungo*)	6 min	Low pressure	Air	Dielectric-barrier discharge	5 kV, 4.5 kHz	Enhanced germination of seeds	(44)
9.	Groundnut (*Arachis hypogae*)	15 s	Low pressure	Helium	Corona discharge, radio frequency	13.56 MHz, 60 – 140 W	Increased yield, growth and germination of seeds	(31)
10.	Rapeseed (*Brassica napus*)	3 min	Atmospheric pressure	Air	Corona discharge plasma jet	20 kV, 58 kHz	Enhanced disease resistance and seed germination	(96)
11.	Sunflower (*Helianthus annuus*)	1min	Atmospheric pressure	Argon, oxygen	Plasma flashlight	8, 10, 12 and 14 kV	Enhanced development and germination of seeds	(97)
12.	Pepper (*Piper nigrum*)	60 s	Low pressure	Air	Radio frequency inductive	13.56 MHz, 18W	Enhance seed coat for healthier germination	(98)
13.	Basil (*Ocimum basilicum*)	10 min	Low pressure	Argon, oxygen	Radio frequency	13.56 MHz, 300 W	Enhanced establishment of seedlings and seed development	(83)
14.	Mimosa (*Mimosa Caesalpiniafolia*)	3 min	Atmospheric pressure	Air, argon	Dielectric-barrier discharge	17.5 kV, 990 Hz	Enhanced wettability and germination of seeds	(99)
15.	Cotton (*Gossypium hirsutum*)	3 min	Atmospheric pressure	Air, neon	Dielectric-barrier discharge	19 kV, 1 kHz	Enhanced seed coat for a more robust germination	(100)

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Authors' contributions

MB searched, collected and wrote the first draft. CM analysed the manuscript, provided the regular assistance to revise and finalize it. MB, CM along with AY reviewed and edited the manuscript. AY, CV and RR critically reviewed and edited the same. All authors have read and approved to publish the manuscript.

Compliance with ethical standards

Conflict of interest: The author declare that there are no conflict of interest

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