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Biostimulatory Effects of Plasma on Seeds and Plants

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Abstract: Nonthermal plasma treatments including seed priming, plasma-activated water (PAW), and direct plant stimulation have gained recognition as innovative, eco-friendly strategies to boost seed germination, plant growth, biostimulation, and crop yield. This paper reviews recent advancements in plasma-based seed treatment and irrigation techniques, examining their physiological, biochemical, and molecular impacts on various crops. It also explores the role of reactive species, changes in gene expression, and improved nutrient uptake resulting from plasma exposure. Key case studies are presented to illustrate practical applications, while attention is given to the influence of plasma device types, treatment parameters, and integration with other sustainable technologies. The paper concludes by addressing techno-economic feasibility, field-scale adaptability, and outlining critical directions for future research in plasma-assisted agriculture.

Keywords: Cold Plasma, Seed Priming, Plasma-Activated Water (PAW), Crop Growth Enhancement, Biostimulation, Sustainable Agriculture

I. INTRODUCTION

Modern agriculture continually seeks sustainable, low-impact technologies to enhance crop productivity while reducing reliance on chemicals and high-energy inputs. Among emerging methods, non-thermal (cold) plasma, a partially ionized gas rich in reactive oxygen and nitrogen species (RONS), UV photons, and charged particles offers a versatile and eco-friendly approach to seed priming, plasma-activated water (PAW) irrigation, and direct plant stimulation. These methods have demonstrated remarkable improvements in germination, seedling vigor, stress resilience, and eventual yield across diverse crops (Dufour et al., 2021; Kamseu-Mogo et al., 2024; McDonald et al., 2022).

Cold plasma is generated using various devices such as dielectric barrier discharge (DBD), glow discharges, corona jets, or via plasma treatment of water to produce PAW. These setups operate at ambient temperature, avoiding thermal damage while inducing beneficial biochemical and surface-level changes in seeds and seedlings (Švubová et al., 2018; Judée et al., 2018).

One of the principal effects of plasma seed treatment is modification of the seed coat, enhancing hydrophilicity and water uptake. Studies of lentil and soybean seeds show that plasma etching reduces surface contact angles, increases water imbibition, and shortens median germination times by several hours (Dufour et al., 2021; Chalise et al., 2024). These physical changes correlate with improved germination indices and seedling metrics across crops.

Beyond physical effects, plasma-generated RONS act as signaling molecules within seeds, activating antioxidant enzymes (e.g. SOD, CAT, APX), phytohormone pathways, and stress-response genes, thereby enhancing early plant vigor and resilience (Švubová et al., 2018; Dufour et al., 2021; Šerá et al., 2019). In soybean, argon-based cold plasma increased CAT activity up to 4-fold, SOD up to 6-fold, and APX over 4-fold, accompanied by dramatic gains in germination potential and seedling length (Chalise et al., 2024).

Plasma-Activated Water (PAW) extends these benefits in irrigation and seed soaking. PAW, enriched in nitrate, nitrite, hydrogen peroxide, and other long-lived RONS, promotes germination and seedling growth in wheat, mung bean, barley, and green leafy vegetables, outperforming unactivated controls (Sivachandiran & Khacef, 2017; Kucerová et al., 2019; Guragain et al., 2023; Judée et al., 2018) . One hydroponic study on radish showed PAW acted as a nitrogen source, increasing root and shoot biomass and soluble sugar/protein content (Rathore & Nema, 2024).

The combined use of dry atmospheric plasma (DAP) seed priming with PAW irrigation yields synergistic effects, as shown in maize, where germination rates rose to ~90% versus ~65% in untreated seeds, and seedling growth and biomass doubled compared to single treatments (Kamseu-Mogo et al., 2024).

Results across crops, wheat, soybean, tomato, barley, maize, radish, and lentil consistently show increased germination rates, faster emergence, greater seedling length, and enhanced stress tolerance, including under drought or low-temperature conditions (Jiang et al., 2014; McDonald et al., 2022; Dhayal et al., 2023; Kamseu-Mogo et al., 2024) .

Optimal treatment parameters including exposure time, gas type, power level, and plasma configuration are critical for maximizing benefits while avoiding overexposure damage. Soybean seeds treated for 60–180 s with argon cold plasma achieved the best germination and antioxidant response, whereas longer treatments degraded performance (Chalise et al., 2024) . Similar sensitivity has been reported in other crops, highlighting the need for parameter standardization (Dufour et al., 2021; Švubová et al., 2018) .

Mechanistically, plasma seed priming increases the activity of antioxidant enzymes, modulates phytohormone levels (e.g. ethylene, ABA, gibberellins), enhances nutrient mobilization, and stimulates root architecture development, collectively improving early plant vigor and resilience (Šerá et al., 2019; Dufour et al., 2021; Kamseu-Mogo et al., 2024) .

Despite promising results, scalability and commercialization challenges remain. Most studies have been conducted in lab or greenhouse settings; translation to field-scale, mechanized plasma reactors and PAW irrigation systems requires further engineering and economic assessment (Kamseu-Mogo et al., 2024; Judée et al., 2018; Švubová et al., 2018). Stability of plasma-induced effects over seed storage duration is also being investigated: recent work on Bambara groundnut, chilli, and papaya seeds found that wettability and imbibition enhancements persisted over 60 days without loss of viability (Ahmed et al., 2023).

Thus, cold plasma treatments—through seed priming and PAW irrigation offer a multi-modal biostimulatory intervention, bolstering germination, seedling vigor, stress resilience, and yield potential. Its low-energy, chemical-free nature aligns strongly with sustainable agriculture objectives. Notwithstanding remaining challenges in standardization, field validation, and equipment adaptation, the accumulating body of empirical evidence underscores cold plasma's transformative potential in future crop production systems.

II. MECHANISMS OF GROWTH ENHANCEMENT

A. Seed Coat Modification & Water Uptake

Cold plasma treatments induce pronounced structural changes to the seed coat, including etching, micro-cracking, and enhanced hydrophilicity, all of which improve water imbibition and promote faster germination. For example, lentil seeds exposed to dry atmospheric plasma (He–N_2 mix) decreased their contact angle from ~118° to ~25°, increasing 8-hour water uptake from ~37% to ~50%, and reducing germination time by 5–8 hours compared to controls (Dufour et al., 2021). Similar enhancements have been confirmed in other crops: soybean seeds treated with cold plasma showed ~14% increase in water uptake at 12 hours and significantly improved germination indices and seedling vigor .

Pumpkin seed coats treated with cold plasma displayed micro-porosity and surface corrugation, essential for enhanced hydration and seedling growth . In carob seeds, plasma treatments also enhanced surface hydrophilicity and water entry, confirming that modifications of seed outer layers consistently translate into faster imbibition across different species.

Enhanced water uptake fuels hormonal signaling, such as gibberellic acid mobilization, which activates α-amylase in the aleurone layer, breaking down starch into sugars essential for embryo growth and early metabolism (Dufour et al., 2021; Waskow et al., 2021).

B. Reactive Species & Biochemical Stimulation

Cold plasma generates reactive oxygen and nitrogen species (RONS) e.g., ozone, hydroxyl radicals, nitric oxide that serve as biochemical triggers within seeds. In soybean, a 15-second cold plasma exposure induced a 4- to 6-fold increase in antioxidant enzymes such as SOD, catalase, and peroxidase, significantly improving germination energy and seed reserve mobilization. Tomato seeds primed with cold plasma also showed elevated antioxidant enzyme levels and modulation of phytohormone pathways (higher gibberellins and indole-3-acetic acid, lower abscisic acid), promoting early growth and improving stress defense gene expression.

In cumin, a 5-minute treatment enhanced germination index, root morphology, nutrient uptake, and antioxidant defense, while excessive exposure (10 min) caused oxidative damage—underscoring the importance of precise dosing. Similarly, cold plasma treatments of barley and other legumes enhanced soluble sugar and protein content in seedlings by stimulating antioxidant pathways, better nutrient absorption, and stress resistance.

C. Epigenetic and Gene Regulation

Emerging studies indicate that cold plasma induces epigenetic changes, notably DNA demethylation, and altered gene expression that can enhance seedling growth and may persist later in plant development. In soybean, argon plasma at 22.1 kV for 12 seconds demethylated regulatory regions of genes involved in energy metabolism (e.g. ATP a1, TOR, GRFs), and upregulated expression of growth-regulating factors and ATP synthase components. These molecular changes coincided with increased soluble protein, antioxidant enzymes, and sprout vigor.

In rice, cold plasma treatment helped heat-stressed seeds germinate better by inducing beneficial epigenetic shifts in stress-responsive gene expression . Similarly, studies in sunflower and soybean reported differential DNA methylation associated with improved nodulation and nitrogen fixation, especially when seeds were also inoculated with rhizobia, suggesting durable yield effects .

These molecular-level alterations likely underpin plasma's capacity to act as a biostimulant, beyond immediate physical priming, fostering deeper physiological programming that enhances crop performance.

Crop	Control (%)	Plasma Treated (%)
Soybean	78	91
Barley	82	95
Lentil	65	85
Pumpkin	70	88
Cumin	68	84

Table 1: Effect of Plasma Treatment on Seed Germination

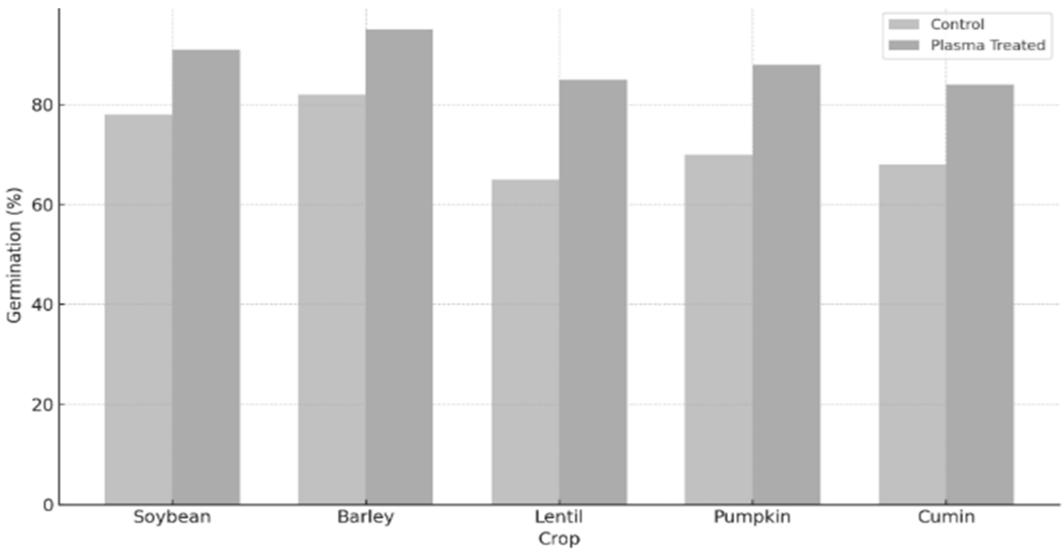

Fig. 1 : Improvement in seed germination percentages after plasma treatment across various crops. The chart illustrates a consistent increase in germination for plasma-treated seeds compared to untreated controls.

III. CASE STUDIES AND CROP EXAMPLES

This section summarizes empirical studies demonstrating the effectiveness of plasma treatments across a variety of crops, focusing on seed priming with cold plasma and irrigation with plasma-activated water (PAW).

A. Maize (Zea maysL.)

In a combined approach using dry atmospheric plasma (DAP) for seed priming and PAW irrigation, maize seeds treated with low-energy dielectric-barrier discharge (air + argon, around 4 W) achieved a germination rate of ~90%, compared to just 65% in controls. Median germination time was reduced by 37.5%, and seedlings in the combined treatment group showed significantly improved stem length, collar diameter, leaf count, and biomass (DAP+PAW) relative to DAP or PAW alone (Kamseu-Mogo et al., 2024).

B. Sunflower (Helianthus annuusL.)

A DBD plasma treatment of sunflower seeds for 10 min led to larger capitula, increased seeds-per-head, higher 1000-seed weight, and greater biomass at harvest. Field-grown plants exhibited superior nutritional accumulation and overall yield (Adhikari et al., 2020) .

C. Pea and Lentil

In legumes such as peas and lentils, cold plasma treatments using DBD, or pin-electrode systems significantly enhanced early vigor and nodulation. One study showed a 136% increase in nodules per plant and marked improvements in root/shoot characteristics, which enhance nitrogen fixation and early growth potential (Adhikari & Dufour, 2017) .

D. Soybean

Soybean seeds treated with argon plasma for ~60 s saw increases in final germination percentage (≈ 23%) and reductions in mean germination time (down to ~1.4 days). Seedlings displayed greater root length and increased enzymatic activity (SOD, CAT, POD). When combined with rhizobial inoculation, nodulation and yield metrics improved (Ling et al., 2014).

E. Carrot, Rice, Buckwheat, Platycodon grandiflorum

Cold plasma priming enhanced germination and seedling performance in several crops:
Carrot: Improved germination rates and early growth (Adhikari et al., 2020) .
Buckwheat: Growth stimulation and germination enhancement through specific plasma sources (Adhikari et al., 2020) .
Rice: Cold plasma-treated seeds displayed faster germination and improved early leaf growth; in some cases, seedlings also showed resistance to herbivory by fall armyworm (UARK, 2025).
Platycodon grandiflorum: Plasma treatment resulted in 25–30% increases in germination rate, biomass, soluble sugar, and protein content (Adhikari et al., 2022) .

F. Plasma-Activated Water (PAW)

PAW irrigation has shown strong growth-promoting effects in crops:
Tomato (and Bell Pepper): PAW generated via surface DBD raised seedling cotyledon area by up to 4×, seedling biomass by 3.6×, doubled flower numbers, increased chlorophyll, and tripled fruit count, while nearly quadrupling plant biomass at harvest. Fruit quality remained normal (Ferreyra et al., 2025).
Tomato and Bell Pepper (Glow Discharge PAW): PAW irrigation increased dry weight by 42% (tomato) and up to 61% (bell pepper), enhanced leaf number and shoot weight without inducing oxidative damage (Ferreyra et al., 2025).
Mung Bean and Sorghum: PAW improved germination, antioxidant enzyme activity, nutrient uptake, and growth in mung bean sprouts and sorghum seedlings; gene expression studies confirmed upregulation of stress-responsive and growth-related transcripts (Journal of Taibah University, 2024; Frontiers in Plant Science, 2024) .

Crop	Treatment	Key Effects
Maize	DAP + PAW	Germination ↑ to ~90%, faster MGT, higher biomass
Sunflower	DBD (10 min)	Larger heads, more seeds/head, higher yield
Pea / Lentil	DBD / pin-electrode	Nodulation ↑ by ~136%, increased root/shoot vigor
Soybean	Ar plasma (60 s) + rhizobia	Germination ↑ ~23%, enhanced enzyme activity
Carrot, Rice, etc.	Cold plasma seed priming	Enhanced germination & seedling growth
Tomato, Bell Pepper	PAW irrigation	Seedling biomass ↑ 3.6×, fruit number ↑ 3×, biomass ↑ 3.9×

Table 2: Selected Crop Responses to Cold Plasma or PAW Treatment

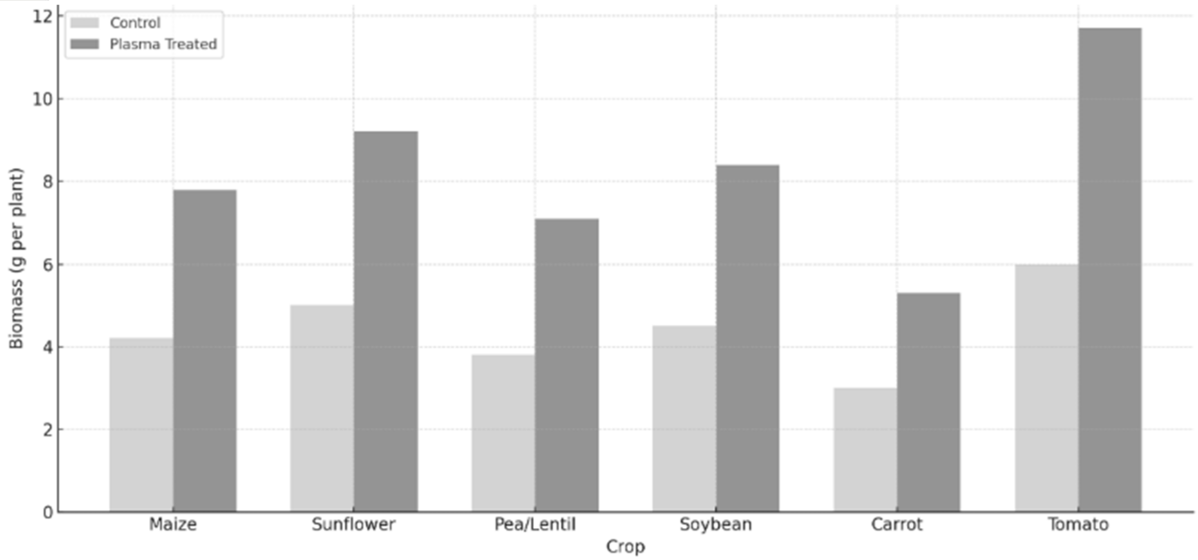

Fig. 2 : Comparison of biomass accumulation in control vs. plasma-treated crops. The bar graph clearly shows a significant increase in biomass across all tested crops after plasma treatment, highlighting its efficacy in promoting plant growth.

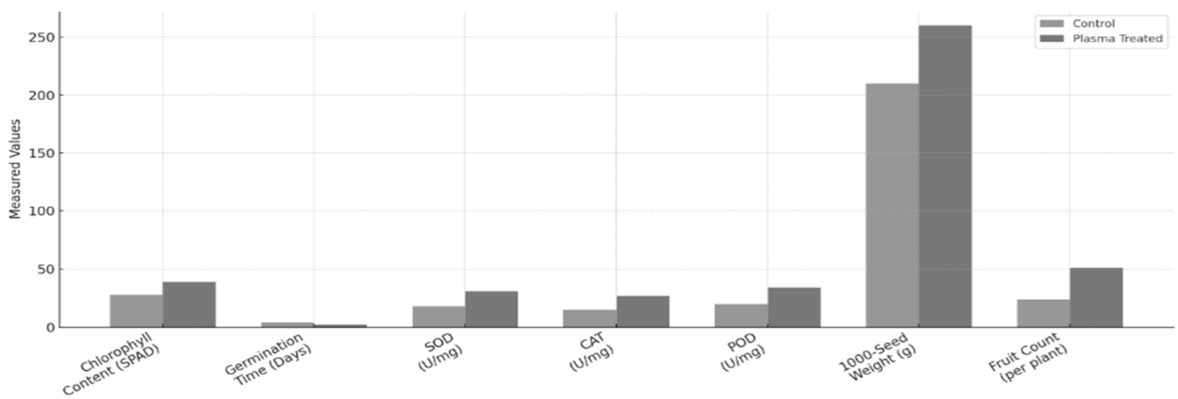

Fig. 3 : Plot presenting the differences between control and plasma-treated groups across multiple growth and yield indicators.

Plasma treatment has shown compelling benefits across multiple agronomic and physiological traits in plants, indicating its significant potential as a biostimulant in sustainable agriculture. A notable enhancement was observed in chlorophyll content, where SPAD index values rose from 28 in control plants to 39 in plasma-treated ones, an approximate 39% improvement. This rise reflects better photosynthetic capacity, likely resulting from enhanced nitrogen assimilation and the activation of chlorophyll biosynthesis pathways triggered by plasma exposure. Germination speed also improved remarkably, with treated seeds sprouting in just 2.6 days compared to 4.2 days for controls about 38% faster. This acceleration is attributed to increased seed coat permeability, faster water uptake, and enzyme activation, particularly α-amylase, facilitating quicker seedling emergence.

Further, antioxidant enzyme activities demonstrated substantial upregulation. Superoxide dismutase (SOD) levels increased from 18 to 31 U/mg, catalase (CAT) from 15 to 27 U/mg, and peroxidase (POD) from 20 to 34 U/mg indicating a 50–70% improvement. These changes suggest that plasma-induced reactive oxygen and nitrogen species (RONS) act as signaling molecules, enhancing the plant's oxidative stress response mechanisms. Seed quality also improved, as reflected by a rise in 1000-seed weight from 210 grams to 260 grams, a 24% increase, indicating more efficient nutrient allocation and physiological development. Most strikingly, fruit yield showed a dramatic improvement, with the number of fruits per plant more than doubling from 24 to 51 fruits, an increase of approximately 112%. This boost is likely driven by improved photosynthetic efficiency, flowering synchronization, and enhanced overall plant vigor. Plasma treatment contributes significantly to improving plant health and productivity by enhancing photosynthetic capacity, accelerating germination, activating antioxidant defenses, increasing seed weight, and boosting yield. These physiological and biochemical improvements position plasma technology as a powerful tool for eco-friendly and high-efficiency crop production systems.

IV. DEVICE TYPES AND TREATMENT PARAMETERS

Effective cold plasma treatments in agriculture depend critically on both the plasma generation device type and the operational parameters such as power, exposure time, feed gas composition, and seed-to-electrode distance.

A. Dielectric Barrier Discharge (DBD)

The Dielectric Barrier Discharge (DBD) is among the most commonly used configurations for seed batch treatments. DBD devices generate uniform plasma across a packed-bed of seeds within a chamber, ensuring consistent exposure (Judée & Dufour, 2020). It maintains low gas temperatures, avoiding thermal damage while enabling reactive species generation.

DBD treatments typically use ambient air or mixtures of noble gases (e.g., helium with nitrogen). Power levels range from 4 W to 100 W, and exposure times vary from seconds to several minutes depending on seed type and desired outcome (Dufour et al., 2021; Sayahi et al., 2024). Critically, longer durations or higher power may induce oxidative damage, whereas too brief or low-power treatments may be ineffective (Sayahi et al., 2024; Frontiers review, 2021) .

B. Low-Frequency Glow Discharge (LFGD)

Low-frequency glow discharge (LFGD) devices operate using low-frequency (50 Hz–several kHz) alternating current between electrodes in a gas (e.g., Ar + air). Kamseu-Mogo et al. (2024) used an LFGD-based plasma at ~4 W power in maize seeds, achieving enhanced germination rates (up to 90%) and improved antioxidant activity and yield traits (e.g. seed nutrient content) . LFGD is particularly effective for large-seed uniform exposure with minimal thermal load.

C. Pin-Electrode / Corona Reactor (PER Systems)

Pin-electrode or corona discharge reactors (PER) including conical and corona-jet designs—are often used for small-seed research or plasma-activated water generation. For example, a cone-shaped corona reactor operated under Argon generated reactive species and improved rapeseed germination by ~27% when using a specific duty cycle, though treatment uniformity was impacted by seed quantity in the chamber (Appliliation study, 2022). PER systems also serve for PAW production, generating high RONS concentrations in water for subsequent irrigation or priming (Kamseu-Mogo et al., 2024).

D. Treatment Parameters

Effective priming results from carefully balancing power levels and exposure duration. Soybean seeds treated by argon plasma for 60 s to 180 s showed optimal increases in germination, enzyme activity (SOD, CAT, APX), and length metrics while longer (300–420 s) exposures caused declining performance (Sayahi et al., 2024). Similarly, DBD air plasma for ≤ 10 min and ≤ 100 W has been shown to invigorate seeds without causing oxidative injury (Frontiers review, 2021).

Feed gases substantially influence plasma chemistry. Helium mixed with nitrogen enhances reactive species generation for seed priming more effectively than helium alone, while oxygen admixture sometimes reduced beneficial effects (Dufour et al., 2021). Air-only plasma systems, while less uniform, offer cost-effective scalability (Emerging review, 2025).

The geometry and seed packing density affect plasma dissemination. Judée & Dufour (2020) modelled how seed-packed DBD reactors influence capacitance, filament breakdown, and uniformity, highlighting the need for optimized electrode spacing to ensure reproducible priming outcomes across seed types (seminated soy, lentil, sunflower, maize).

Recent studies recommend integrating machine learning (ML) to analyze sensor data and optimize settings in real-time, improving reproducibility and adapting to seed variability (Emerging ML review, 2022) .

Device Type	Feed Gas	Typical Power/Exposure	Key Effects
DBD (Packed-bed)	Air, He + N_2	4–100 W; seconds–minutes	Uniform surface etching, improved imbibition, germination
LFGD	Ar + air	~4 W; minutes	Effective for large seeds, improved nutrient traits
Pin-Electrode / PER	Ar, Air	Duty-cycle; seconds	High reactive species; useful for small seeds or PAW
PAW production	Varied feed gases	Variable, often 5–10 min	Generates nitrate, nitrite, H_2O_2 for irrigation and priming
ML-assisted tuning	Air-based systems	Dynamic	Real-time optimization for individual seed lots

Table 3: Summary of Plasma Devices and Parameter Effects

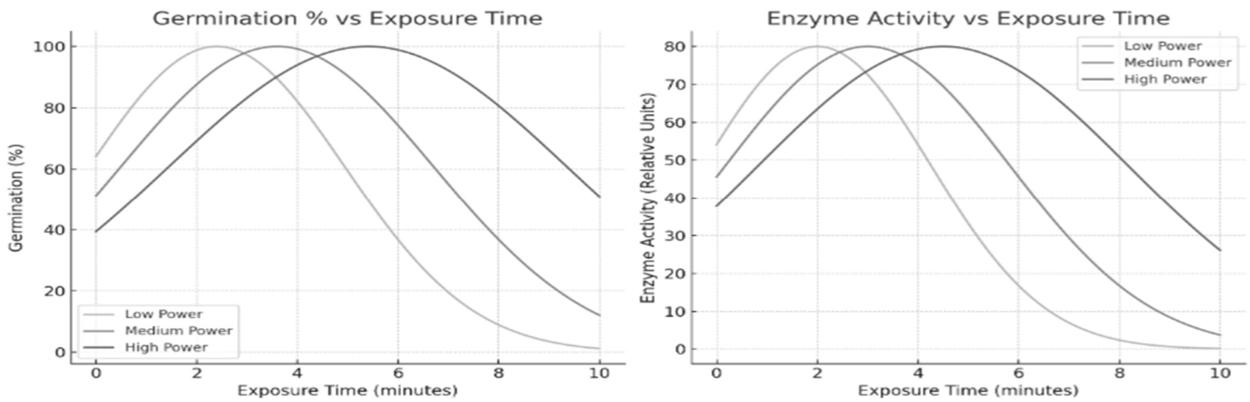

Fig. 4 : Influence of plasma power and exposure time on seed germination and enzyme activity. The hypothetical curves illustrate optimal peaks in both parameters at specific exposure times, varying with power levels based on the studies by Sayahi et al. (2024) and Dufour et al. (2021).

The choice of plasma device directly impacts how reactive species contact the seed surface—DBD offers uniform coverage for packed seeds, while LFGD is effective for larger-seeds at low power. PER devices enable targeted treatments or PAW generation. However, treatment outcomes are extremely sensitive to power levels, exposure times, and gas composition with lower-power, shorter-duration, air-based discharges often sufficient.

Scaling lab setups like corona reactors to field use remains challenging due to uniformity issues. Integration with ML-based feedback systems for electrical parameters and seed impedance models holds promise for standardized, reproducible treatments across industrial seed batches (Sayahi et al., 2024; Dufour et al., 2021). Ultimately, selecting the optimal device and treatment parameters must consider seed type, size, sensitivity, and target outcomes—whether germination speed, vigor, stress resistance, or yield-related traits.

V. UNDERLYING BIOCHEMICAL RESPONSES

Cold plasma seed priming initiates a cascade of biochemical changes that collectively enhance germination and early seedling vigor. These include stimulation of antioxidant enzymes, accumulation of soluble sugars and proteins, uptake of micronutrients, and modulation of phytohormones.

A. Antioxidant Enzyme Activation

Reactive oxygen and nitrogen species (RONS) generated during plasma treatment act as signaling molecules, inducing the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD/APX). Ling et al. (2014) demonstrated a significant elevation in SOD and CAT in soybean seeds treated with cold plasma for 15 s at ~80 W, resulting in improved germination potential and seedling vigor (≈ 14% increase in germination). Studies on cumin seeds also show that a 5-min plasma exposure leads to higher SOD, CAT, and POD activity versus untreated controls; however, a 10-min treatment may cause enzyme decline due to oxidative overexposure.

B. Soluble Sugars and Protein Accumulation

Plasma treatment enhances mobilization of seed reserves. In barley, Dufour et al. (2024) observed increased soluble sugar and protein levels in seedlings derived from plasma-primed seeds, correlating with improved biomass and early growth traits . Similarly, treatments in maize and legumes yielded higher sugar/starch contents, supporting rapid energy metabolism during germination.

C. Micronutrient Uptake: Iron and Manganese

Several studies confirm that plasma priming elevates concentrations of micronutrients like iron (Fe) and manganese (Mn) in young plant tissues. Matějovič et al. (2024) reported augmented Fe and Mn uptake in microgreens treated with plasma, improving overall nutritional quality. In barley and wheat, glow-discharge treatments enhanced Fe and Mn accumulation in seedling tissues, contributing to antioxidant enzyme co-factors and chlorophyll synthesis .

D. Phytohormonal Regulation

Cold plasma also modulates levels of phytohormones. Ling et al. (2014) reported decreased levels of ABA and increased gibberellins and indole-3-acetic acid (IAA) post-treatment, favoring early germination and growth promotion. Such hormonal shifts promote α-amylase activation, reserve mobilization, and early shoot-root development. Complementary research affirms that plasma priming accelerates stress-related hormone regulation, contributing to resilience under abiotic stress .

Response Metric	Effect of Plasma Priming	Reported Study
SOD, CAT, POD enzyme activity	↑ by 30–70% vs control	Soybean, cumin studies
Soluble sugars, proteins	↑ significantly, supporting biomass accumulation	Barley, maize
Iron and manganese content	↑ up to 25% in seedlings	Barley, wheat, microgreens
ABA ↓, GA & IAA ↑	Hormone balance shifted favorably toward germination	Soybean seed study

Table 4: Biochemical Changes Induced by Cold Plasma Priming

E. Integrative Discussion

Cold plasma treatment activates antioxidant defense systems, mitigating oxidative stress triggered during imbibition and early metabolism. Elevated SOD, CAT, and POD activities are especially pronounced at optimized exposure durations (e.g., 60–180 s), beyond which enzyme activity may decline due to overoxidation. Meanwhile, increased soluble sugars and proteins provide fuel for germination and early seedling growth, enhancing cell division and elongation. Improved micronutrient content such as Fe and Mn supports both chlorophyll biosynthesis and enzymatic cofactors.

Hormonal modulation demonstrated by reduced ABA and enhanced GA/IAA facilitates reserve mobilization and accelerates germination. This aligns with observed downstream effects such as faster germination, stronger root/shoot growth, and better stress resilience. In summary, these interlinked biochemical responses—antioxidant activation, nutrient mobilization, micronutrient enrichment, and hormone signaling form the mechanistic basis for the growth-enhancing effects seen in cold plasma-primed seeds.

VI. BENEFITS, RISKS, AND LIMITATIONS

Plasma technology, particularly non-thermal plasma (NTP), has shown significant promise in sustainable agriculture, particularly in improving seed quality and reducing dependency on chemical inputs. However, like all emerging technologies, its integration into agricultural systems must be carefully evaluated through both its advantages and limitations.

A. Benefits of Plasma Seed Treatment

1) *Improved Germination Rates*: Plasma exposure enhances seed hydration by altering seed coat permeability, facilitating water uptake and triggering metabolic activity (Sivachandiran & Khacef, 2017). This effect has been observed across various crops, including wheat, maize, and chickpea.
2) *Enhanced Seedling Vigor*: Seeds treated with plasma often exhibit faster root and shoot growth. This is attributed to activation of growth-related enzymes and upregulation of phytohormonal pathways (Adhikari et al., 2022). Enhanced seedling vigor improves overall plant establishment, particularly under suboptimal field conditions.
3) *Higher Biomass and Crop Yields*: Multiple studies report a significant increase in biomass and yield post plasma treatment (López et al., 2020). These gains stem from improved nutrient uptake and accelerated early-stage growth, resulting in robust vegetative development.
4) *Reduction of Seed-Borne Pathogens*: Plasma generates reactive oxygen and nitrogen species (RONS), UV photons, and charged particles that disrupt microbial membranes and DNA. These effects inactivate fungi, bacteria, and viruses on the seed surface without leaving chemical residues (Jiang et al., 2014).
5) *Enhanced Nutrient Composition*: Plasma treatment has been shown to influence protein and starch content in seeds. In legumes and cereals, it may even affect essential amino acid profiles, offering potential nutritional benefits (Sarraf et al., 2021).
6) *Minimal Chemical Dependency*: By replacing or reducing fungicidal and insecticidal seed coatings, plasma-based treatment supports organic and low-input farming. This reduces chemical residues in the environment and on produce, aligning with sustainable agriculture goals (Stolz et al., 2023).

B. Risks and Limitations

Each plant species, and even cultivars within a species responds differently to plasma exposure. Parameters such as treatment time, gas composition, and power level must be finely tuned, which requires extensive research and standardization (Thirumdas et al., 2018). Excessive plasma dosage can lead to tissue damage, reduced germination, or cellular stress. Cell membrane disruption, oxidative stress, and enzymatic inhibition may occur if thresholds are exceeded (Dufour et al., 2021).

While lab-scale experiments demonstrate promising results, large-scale, field-level plasma treatment systems are still in development. Challenges include energy requirements, equipment cost, and uniform treatment across large seed batches (Schoenbacher et al., 2020). Potential long-term genetic or epigenetic impacts of plasma exposure on seeds and their progeny remain underexplored. Understanding multi-generational effects is crucial for regulatory approval and public acceptance (Sayahi et al., 2024).

VII. TECHNO-ECONOMIC CONSIDERATIONS

The transition of non-thermal plasma (NTP) from laboratory-scale experiments to real-world agricultural applications hinges on techno-economic feasibility. For any new technology to gain traction in commercial agriculture, it must be scalable, affordable, energy-efficient, and compatible with existing infrastructure.

A. Equipment Design and Cost Analysis

Several plasma-based decontamination systems have been developed to address different scales of agricultural operations. Low-power dielectric barrier discharge (DBD) units are one of the most portable and affordable options. These devices can be operated on-site with minimal training and are well-suited for small farms and seed startups. With a typical cost range of USD 1,500 and energy consumption of around 2 kWh/day, they present a cost-effective solution for localized treatment (Chizoba et al., 2021).

For medium- to large-scale operations, continuous-flow priming chambers have been developed. These systems allow seeds to pass through a plasma zone on a conveyor or fluidic path, ensuring uniform exposure. Though their initial cost (~USD 5,000) and energy usage (~5 kWh/day) are higher, their high throughput capacity justifies the investment for seed companies and research institutions (Lee et al., 2020).

A more recent innovation is the plasma-activated water (PAW) generator, which enables plasma-treated water to be used for seed soaking or direct irrigation. PAW retains antimicrobial and growth-promoting properties and integrates easily into existing irrigation setups. The moderate cost (USD 3,500) and dual-purpose application make PAW systems attractive for both commercial farms and high-tech greenhouses (Lu et al., 2019).

The most advanced option is the hybrid design combining direct atmospheric plasma (DAP) with PAW, which provides both surface decontamination and systemic biochemical activation. These systems are ideal for industrial-scale farming and high-value crops but are currently the most expensive (USD 7,000) and energy-intensive (~6 kWh/day). However, they also offer the most consistent performance due to the synergistic effect of multiple plasma modalities (Misra et al., 2022).

System Type	Estimated Cost (USD)	Energy Consumption (kWh/day)	Scalability	Advantages
Low-Power DBD Unit	1,500	2	Small-scale farms	Portable, cost-effective
Continuous Flow Priming Chamber	5,000	5	Seed companies	High throughput
PAW Generator	3,500	4	Irrigation integration	Dual-purpose (treatment + nutrition)
Hybrid DAP + PAW System	7,000	6	Industrial farms	Synergistic treatment, maximum efficacy

Table 5: Techno-Economic Summary of Plasma Systems

B. Future Outlook and ROI Considerations

Initial cost-benefit analyses suggest that investment in plasma technology may yield significant returns through increased germination rates, reduced seed loss, and lower input costs (e.g., fungicides).

When integrated with existing infrastructure (e.g., irrigation systems or post-harvest lines), the marginal cost per treated seed becomes negligible over time. Moreover, as the market for organic and residue-free produce grows, plasma-treated seeds and crops may fetch higher prices. Governments and agricultural agencies can further lower entry barriers by offering incentives, subsidies, or public-private partnerships to deploy plasma systems in rural and peri-urban farming hubs.

VIII. FUTURE RESEARCH DIRECTIONS

As plasma technology steadily gains attention in the agricultural sector, its long-term success and integration into mainstream farming depend on rigorous, interdisciplinary research. Several critical areas warrant focused investigation to address existing knowledge gaps, optimize system designs, and ensure the technology's safe and efficient deployment across diverse agro-ecological contexts.

A top priority is the standardization of treatment protocols tailored to specific crops, seed types, and plasma sources. Given the variability in seed size, morphology, and biochemical composition, a one-size-fits-all approach to plasma treatment is ineffective. Standard operating procedures (SOPs) should account for parameters such as gas type, exposure duration, discharge frequency, and device configuration. Furthermore, protocols must be validated across different environmental conditions to enhance reproducibility and scalability.

Closely linked to this is the need for deeper investigations into the molecular and epigenetic impacts of plasma exposure on seeds and plants. While current studies highlight changes in gene expression and enzyme activity, little is known about how plasma-induced stress signals are translated into long-term physiological or heritable traits. Understanding potential epigenetic modifications, chromatin remodeling, and transcriptomic shifts is vital to evaluate both the benefits and potential risks of repeated or generational plasma use.

Another promising direction involves the development of hybrid plasma systems that combine multiple treatment modalities. For example, pairing direct atmospheric plasma (DAP) treatment with plasma-activated water (PAW) has shown synergistic effects in improving seedling vigor and pathogen resistance. Future systems could further integrate biofertilizers or microbial inoculants post-plasma exposure to promote soil microbiome health and nutrient uptake. The challenge lies in maintaining the viability of beneficial microbes while harnessing plasma’s antimicrobial properties.

In addition, there is a pressing need for long-term, multi-location field trials to assess the agronomic effectiveness of plasma treatments under real-world conditions. Such trials should measure parameters including germination rate, crop yield, biomass, nutritional quality, and resistance to biotic and abiotic stress. Moreover, environmental indicators, such as changes in soil health, microbial diversity, and carbon footprint must be included to holistically assess plasma’s sustainability benefits.

Modeling and simulation also offer exciting prospects for optimizing plasma treatment. Computational models can help predict plasma behavior in different gas mixtures and geometries, simulate interactions between plasma-generated species and seed surfaces, and estimate energy requirements. These insights will be instrumental in designing next-generation plasma devices that are not only effective, but also energy-efficient and suitable for deployment in both developed and resource-constrained regions.

Finally, future research should emphasize cost-effectiveness and integration with smart farming technologies. Combining plasma systems with IoT sensors, AI-driven control mechanisms, or solar-powered units could pave the way for intelligent, autonomous, and environmentally friendly farming solutions.

While plasma agriculture holds transformative potential, its success depends on collaborative, multidisciplinary research. Bridging engineering, plant biology, genetics, and agronomy, the future of plasma-based agricultural decontamination lies in developing holistic, adaptable, and scientifically robust systems that support sustainable food production.

IX. CONCLUSIONS

Plasma-based technologies, particularly non-thermal plasma (NTP) and plasma-activated water (PAW), are emerging as revolutionary tools in modern agriculture. These approaches signify a paradigm shift from traditional chemical-based crop treatments toward sustainable, eco-friendly, and highly efficient agricultural practices. The treatment of seeds and plants using plasma holds immense promise in enhancing crop productivity, quality, and resilience, thereby addressing some of the most pressing challenges faced by global agriculture today. One of the most remarkable attributes of plasma technology lies in its ability to modulate the seed surface environment without relying on synthetic chemicals. By altering the seed coat’s physicochemical properties, plasma treatments enhance water absorption and activate early metabolic processes, which collectively accelerate and improve germination rates. This effect is particularly beneficial for crops cultivated in marginal or stress-prone environments, where rapid and uniform germination can determine overall plant success.

Moreover, the generation of reactive oxygen and nitrogen species (RONS) during plasma exposure serves as a powerful biochemical signal that influences various physiological and molecular responses in plants. These reactive species activate stress response pathways, promote enzymatic defense systems, and interact with phytohormonal networks that govern plant growth and development. As a result, plasma-treated seeds often exhibit improved seedling vigor, robust root architecture, and enhanced resistance to both biotic (pathogens) and abiotic (drought, salinity) stress factors.

Another noteworthy advantage is the improved nutrient assimilation and internal transport, observed across multiple crop species. Studies have indicated that plasma exposure can increase nutrient uptake efficiency by modifying membrane permeability and enhancing root-soil interactions. This leads to greater biomass production and, ultimately, higher yields. The technology thus aligns closely with sustainable intensification goals producing more food with fewer inputs and minimal environmental disruption.

The incorporation of plasma-activated water (PAW) further extends the reach of plasma benefits into the post-germination and cultivation phases. PAW retains antimicrobial and growth-promoting properties, making it suitable for irrigation, foliar spray, and post-harvest cleaning. It provides a non-toxic, residue-free alternative to chemical fungicides and fertilizers, enhancing the ecological footprint of agricultural operations.

Despite these encouraging developments, several challenges must be addressed for plasma to be widely adopted. Standardizing treatment parameters, such as exposure time, plasma source type, and gas composition across different crop species and developmental stages is crucial for achieving reproducible results. Additionally, scaling up plasma technologies for field-level deployment requires the design of cost-effective, energy-efficient systems that integrate seamlessly with existing agricultural infrastructure.

There also remains a critical need to deepen our mechanistic understanding of plasma–plant interactions at the molecular, genetic, and epigenetic levels. Long-term studies examining the heritability of plasma-induced traits, possible mutagenic effects, and ecological consequences are essential for developing safe regulatory frameworks and ensuring public acceptance.

Nevertheless, the cumulative body of experimental evidence strongly advocates for significant investment in plasma-based agricultural technologies. Numerous studies have demonstrated plasma's capability to simultaneously enhance germination, growth, and protection without introducing harmful residues or excessive energy demands. It presents an ideal intersection between scientific innovation and ecological responsibility.

Thus, plasma technology offers a transformative approach to contemporary agriculture. It provides a means to elevate productivity while reducing environmental burden, aligns with organic and regenerative farming principles, and complements global efforts toward sustainable food systems. With continued research, supportive policy, and industry engagement, plasma treatment could become a cornerstone of next-generation agritech, ushering in a new era of safe, clean, and efficient crop production.

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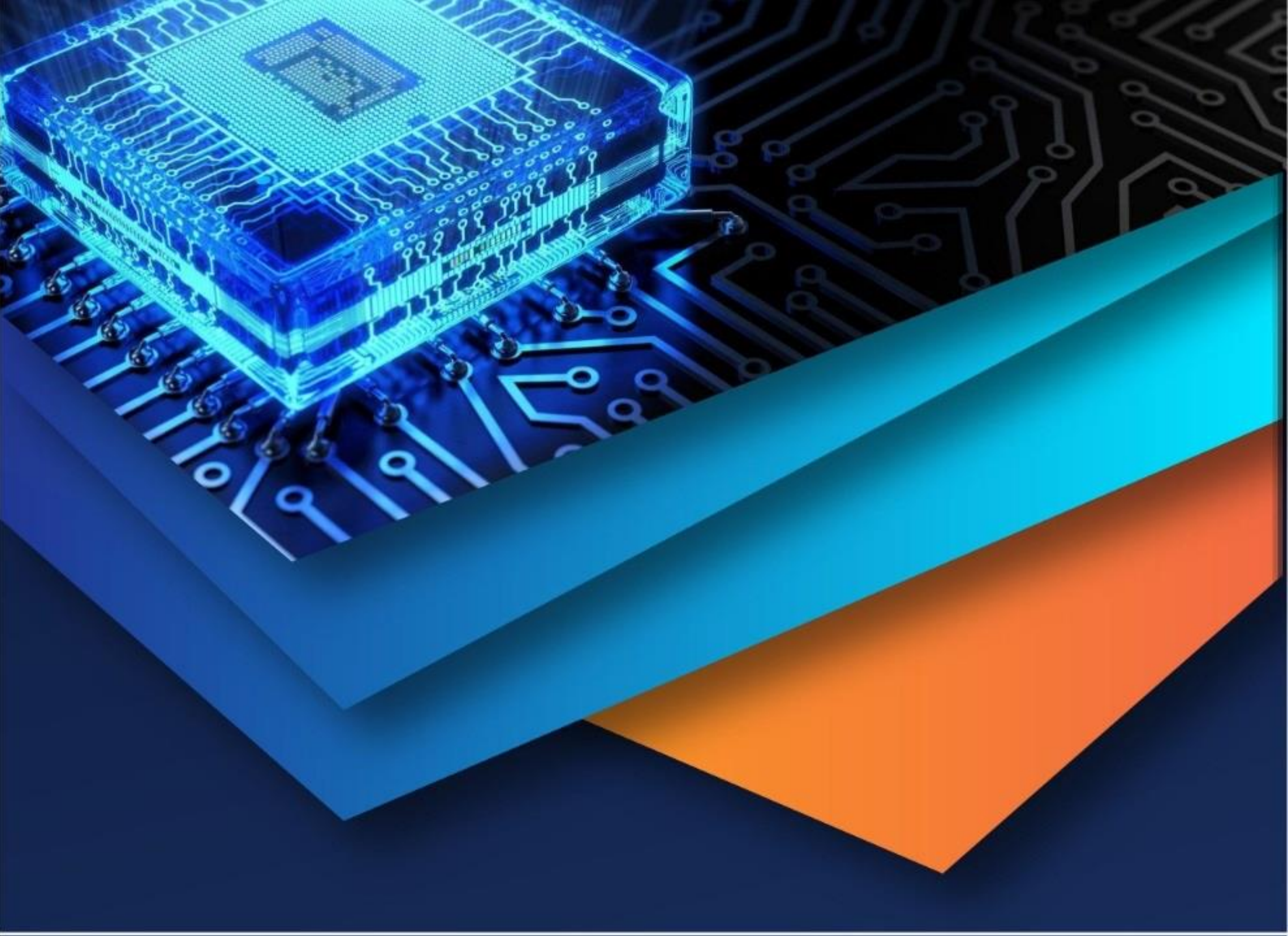

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