MECHANISM AND EFFICACY EVALUATION OF ATMOSPHERIC PRESSURE DBD PLASMA TREATMENT FOR FORAGE GRASS SEEDS
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面向牧草种子应用的常压 DBD 等离子体种子处理机制与效能评估

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ABSTRACT
To overcome the problems of low germination rate and irregular emergence caused by dense surface structure, poor water permeability, and dormancy of forage seeds, this study screened the optimal plasma generation mode suitable for continuous treatment of forage seeds under atmospheric pressure and evaluated its efficacy and mechanism. Through a comparative analysis of the uniformity and stability of corona, spark, gliding arc, and dielectric barrier discharge (DBD), the results showed that DBD can generate large-area, low-temperature, and uniform plasma in atmospheric air. Taking Leymus chinensis seeds as the research object, the effects of different treatment voltages (0–16 kV) on the glume microstructure and the electrical conductivity of the leachate were investigated. Scanning electron microscopy (SEM) observations indicated that DBD treatment with appropriate parameters caused significant etching on the seed glume surface, forming micropores and fissures, and removing impurities. The electrical conductivity measurements further revealed a “dosage effect”: moderate voltage helped maintain the integrity of the membrane system, whereas excessive voltage led to severe damage to the glume and leakage of intracellular contents. The study confirmed that atmospheric pressure DBD plasma, through physical etching and surface modification, can effectively improve the water absorption channels and physiological activity of Leymus chinensis seeds, and an optimal parameter window exists. These findings provide a technical basis for the development of continuous plasma seed treatment equipment.

摘要
为克服牧草种子因表面结构致密、透水性差及休眠特性导致的萌发率低、出苗不齐等问题，本研究筛选适用于常压条件下牧草种子连续处理的最佳等离子体发生方式，并评估其效能与作用机制。通过对比电晕、火花、滑动电弧及介质阻挡放电（DBD）的均匀性与稳定性，结果显示，DBD 可在常压空气中产生大面积、低温、均匀等离子体。以羊草种子为对象，探究不同电压（0–16 kV）处理对其颖壳微观结构及浸提液电导率的影响。扫描电镜观察表明，适宜参数的 DBD 处理可使种子颖壳表面产生显著刻蚀，形成微孔与裂隙，并清除杂质；电导率测定结果进一步揭示了“剂量效应”：中低电压有助于维持膜系统完整性，过高电压则导致颖壳过度损伤及内含物外渗。研究证实，常压 DBD 等离子体通过物理刻蚀与表面改性，可有效改善羊草种子的吸水通道与生理活性，且存在最优处理参数窗口。研究结果为开发连续式等离子体种子处理装备提供了技术依据。

INTRODUCTION
Superior forage seeds constitute the material basis for ecological restoration, pasture management, and urban greening (*Fekete et al., 2024*). However, a substantial number of dominant grass species are characterized by inherent physiological defects, such as hard and dense seed coats, poor water and air permeability, and deep dormancy. These characteristics inevitably lead to slow germination, irregular seedling emergence, and low seedling rates under natural conditions, thereby severely restricting their efficient utilization (*Harrison et al., 2025*). Although traditional physical or chemical treatment methods—such as mechanical scarification, concentrated sulfuric acid treatment, and hormone soaking—have demonstrated certain efficacy, they are associated with significant drawbacks.

These include uneven treatment, potential damage to the embryonic body, chemical residue pollution, and difficulties in scaling up. Consequently, these conventional approaches fail to fundamentally meet the new requirements for high efficiency, safety, and environmental protection demanded by modern green agriculture and ecological construction.

In recent years, various physical pre-sowing treatments have been explored to overcome seed dormancy and improve germination. For instance, pulsed electric fields (*Evrendilek et al., 2021*; *Hou et al., 2023*; *Song et al., 2025*) and electromagnetic treatment (*Ganeva et al., 2015; Pentoś et al., 2024*) have been reported to enhance seed germination and stress tolerance by affecting membrane potential and ion transport. However, these methods primarily rely on electric or magnetic forces without altering the seed coat's physical structure or surface chemistry. As a modern physical agricultural high-technology, low-temperature plasma has been introduced within the rapidly developing field of Plasma Agriculture, offering distinct advantages (*Waskow et al., 2021*; *Hui et al., 2025*). Research indicates that reactive species and ultraviolet radiation from plasma can etch seed coats, enhance hydrophilicity, and induce biostimulation (*Attri et al., 2023*; *Benabderrahim et al., 2025*). Various plasma technologies have been applied to seed treatment: corona discharge on alfalfa seeds reduced contact angle and increased water absorption (*Xu et al., 2021*); cold plasma jet on oat seeds improved germination under salt stress (*Zhang et al., 2024*); transient spark discharge restored germination of fungus-infected wheat seeds (*Doshi et al., 2024*); gliding arc discharge inactivated pathogens on Astragalus seeds while increasing germination rate (*Liu et al., 2021*).

Despite these confirmations, a systematic comparison of different atmospheric plasma generation modes for forage seed treatment is still lacking. Most studies focus on single technologies without evaluating their uniformity, continuity, and suitability for large-scale, continuous seed processing. Therefore, the research gap addressed by this paper is the need to identify the optimal plasma generation mode for continuous, non-damaging treatment of forage seeds under atmospheric pressure.

To address this gap, this study provides a side-by-side comparison of corona, spark, gliding arc, and DBD for seed treatment, identifies DBD as the preferred mode for continuous processing, and systematically evaluates the dosage effect on seed coat microstructure and membrane integrity, thereby establishing a technical basis for equipment development. Accordingly, the core hypothesis is that under atmospheric pressure, DBD plasma represents the optimal technical route for overcoming the inherent defects of grass seeds and achieving efficient continuous treatment.

MATERIALS AND METHODS

1 Comparative Experiment on Atmospheric Pressure Plasma Generation Modes

Based on the different configurations of electrodes, gas discharge generates plasma in various forms. Common discharge modes include corona discharge, spark discharge, glow discharge, Dielectric Barrier Discharge (DBD), and gliding arc discharge (*Wang et al., 2025*). To screen for an atmospheric pressure plasma generation mode suitable for continuous seed treatment, experimental test benches corresponding to each discharge principle were established. The experiments were conducted under ambient temperature and pressure conditions using seeds as the treatment object. By directly observing the discharge phenomena and seed status, the plasma generation modes were qualitatively evaluated from the perspectives of discharge uniformity and continuity, the stability of the discharge state upon seed introduction, thermal effects within the discharge region, and the risk of physical damage to the seeds (*Mazandarani et al., 2020*).

2 Evaluation Experiment of Plasma Treatment on Seed Performance

Upon determining the optimal atmospheric pressure plasma generation mode, an integrated plasma forage seed treatment prototype was developed based on the experimental setup to verify the feasibility of continuous treatment. Wild *Leymus chinensis* seeds, a typical gramineous forage, were selected as the experimental material and processed using this prototype.

2.1 Experimental Design for Plasma Seed Treatment

The DBD device used a plate-to-plate electrode configuration with a quartz glass dielectric barrier. The discharge gap was fixed at 6 mm, and the dimensions of each electrode plate were 150 mm × 150 mm. The power supply (CTP-2000K) operated at an AC frequency of 1–100 kHz (adjustable) and provided an output voltage from 0 to 30 kV.

Six discharge voltage levels were applied: 0 (control), 3, 6, 10, 13, and 16 kV. These values were selected to cover a wide range from weak to intense discharge, based on the adjustable capability of the power supply and preliminary observations of discharge stability. A fixed treatment time of 20 s was chosen for voltage effect tests, as suggested by preliminary experiments and prior work (*Tang et al., 2017*).

2.2 Assessment of Plasma Seed Treatment Performance

(1) Scanning Electron Microscopy (SEM) Test

To systematically elucidate the plasma seed treatment mechanism, specifically the physical etching and surface modification effects of DBD plasma on the seed coat of *Leymus chinensis*, high-resolution morphological observations were conducted using a scanning electron microscope (SU3500, Hitachi High-Tech Corporation). Samples were taken from untreated seeds and seeds treated with plasma at different voltages (3, 6, 10, 13, and 16 kV). The seeds were positioned at various orientations on the sample stage to facilitate the observation of different morphological features. For *Leymus chinensis* seeds, observations were required for the central protrusion, depressions, and edge bristles. The smooth surfaces and awns were observed at magnifications of 300x and 500x, respectively. The changes in surface particles, cracks, gaps, pores, and impurity contaminants on the seed coat were focused on and recorded to visualize the structural alterations under different discharge voltages.

(2) Electrical Conductivity Test

Electrical conductivity measurement was utilized to analyze the ion permeability of the seed leachate. Seeds treated at different voltages (0, 3, 6, 10, 13, and 16 kV) were divided into groups, with 40 seeds per group, and placed in beakers containing 50 mL of deionized water to ensure complete immersion. At a room temperature of 25°C, the electrical conductivity of the leachate was measured every 2 hours using a conductivity meter for a continuous duration of 24 hours. The experimental group was repeated 5 times to obtain the average value. By comparing the variation trends of conductivity over time among different treatment groups, the influence of plasma treatment on seed coat membrane permeability and the leakage of endogenous substances was analyzed, thereby revealing the potential dosage effect.

RESULTS AND DISCUSSION

1 Screening Results and Analysis of Plasma Generation Modes

The mode of plasma generation constitutes the core of the design for the seed pre-sowing treatment device, as the characteristics of plasma generated by different gas discharge forms and their effects on seeds vary significantly. Therefore, based on the fundamental principles of various gas discharges, corresponding test benches were designed. By positioning seeds within different forms of electric fields and regulating voltage and current parameters, the differences in discharge phenomena before and after the addition of seeds were systematically compared. The focus was placed on the uniformity and continuity of the discharge under atmospheric pressure, as well as its adaptability to seeds, to screen out the plasma generation mode most suitable for batch and continuous seed treatment in plasma agriculture.

1.1 Gliding Arc Discharge Seed Treatment

Based on the principle of gliding arc discharge, a seed treatment test bench was designed (Fig. 1). The apparatus primarily consists of a radio frequency (RF) power supply, a voltage regulator, an oscilloscope, a fan, electrodes, and a seed treatment section. The discharge component is composed of two high-voltage metal plate electrodes with a phase difference of 180°, mounted on an aluminum alloy frame. A fan is installed directly above the electrodes, while the seed treatment chamber is positioned directly below, with a discharge voltage range of 0–50 kV.

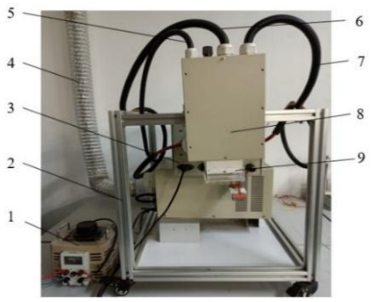
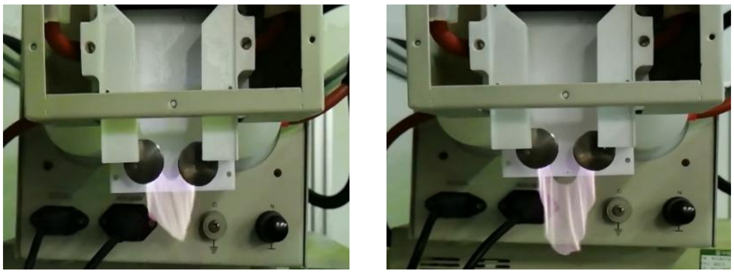


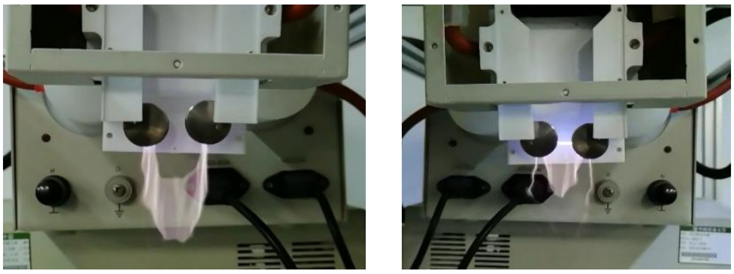
Fig. 1 - Gliding arc discharge seed treatment test bench
1. Voltage regulator; 2. Frame; 3. Discharge power supply; 4. Exhaust pipe; 5. Fan power cable; 6. High-voltage cable A; 7. High-voltage cable B; 8. Fan and electrode; 9. Seed treatment chamber

Observations of the discharge phenomena were conducted by placing different types of seeds in the gliding arc electric field and adjusting the discharge voltage via the regulator. The complete process from generation to extinction of the gliding arc was demonstrated: upon activating the power supply and fan, the gas between the electrodes was broken down, forming an initial arc (Fig. 2a).

Driven by the airflow generated by the fan, the arc moved along the electrode towards the other end and gradually elongated (Fig. 2b and c). When the supplied energy was insufficient to maintain arc propagation and compensate for thermal diffusion losses, the arc was extinguished and subsequently regenerated at the electrode throat, thereby entering the next discharge cycle (Fig. 2d). The discharge process after the addition of alfalfa seeds is shown in Fig. 3. The results indicated that due to the limited action area of the arc and the susceptibility of small-sized seeds to dispersion by strong airflow, this method is difficult to implement for the high-efficiency treatment of large batches of small seeds. Additionally, the high local temperature of the arc is prone to causing thermal damage to the structure of the treatment chamber.



（a） （b）



（c） （d）

Fig. 2 - Generation process of gliding arc discharge

Note: (a), (b), (c) The process of arc diffusion; (d) The phenomenon of the previous arc extinguishing and the subsequent arc generating.

Fig. 3 - Phenomenon of gliding arc discharge seed treatment

1.2 Corona Discharge Seed Treatment

Based on the principle of corona discharge, a needle-to-plate corona discharge seed treatment test bench was designed, as illustrated in Fig. 4. The test bench is primarily composed of a radio frequency (RF) power supply, a voltage regulator, and a seed treatment chamber. The discharge component includes a high-voltage electrode and a grounded electrode. Specifically, the high-voltage electrode consists of a needle electrode fabricated from a conductive screw, whereas the grounded electrode is a flat metal plate. The overall frame structure is constructed using aluminum alloy profiles.

The working principle of the corona discharge test apparatus is described as follows: During the experiment, seeds were spread flat on the grounded electrode plate, and the distance between the needle and plate electrodes was adjusted via a lifting knob. The high-voltage and grounded electrodes were connected to the corresponding terminals of the power supply, respectively. By regulating the voltage parameters of the power supply, the corona discharge phenomena and the state of plasma wrapping around the seeds under different voltages were observed, thereby evaluating the applicability of this discharge form for seed treatment.

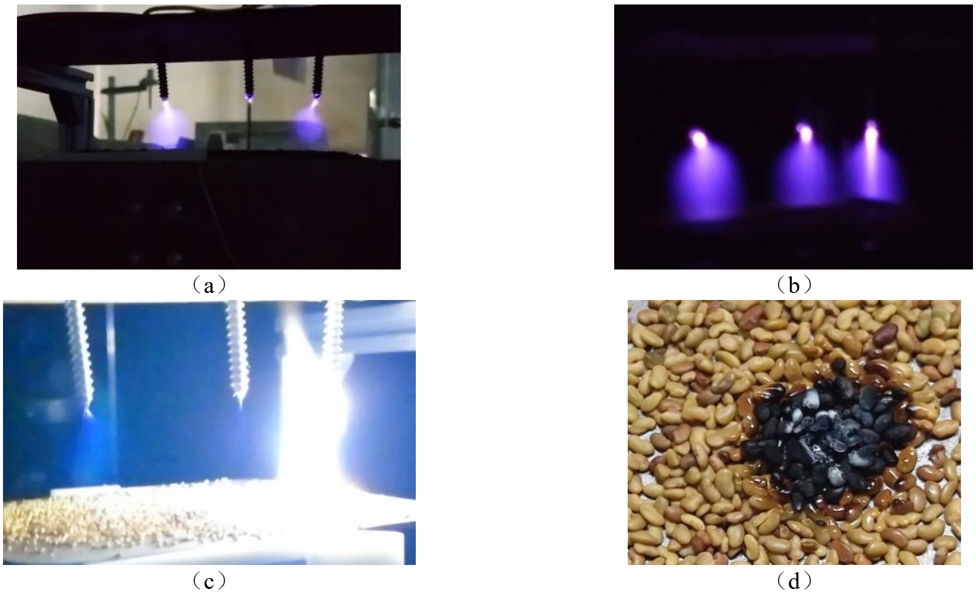


Fig. 4 - Corona discharge seed treatment

Note: (a), (b), (c) Discharge phenomena with gradually increasing discharge voltage; (d) Treatment effect on the seeds at maximum discharge voltage.

At the initial discharge stage, a glow accompanied by a "hissing" sound appeared around the needle electrode, with the current concentrated locally at the needle tip (Fig. 4a). As the voltage increased, localized discharge and halo phenomena emerged (Fig. 4b). When the voltage was further increased (Fig. 4c), significant damage was observed on the seed surface (Fig. 4d). The experiments demonstrated that the current density in corona discharge is highly concentrated at the needle tip, resulting in uneven charge distribution and poor electric field uniformity. Consequently, achieving a uniform plasma wrapping effect on the seed surface was difficult. Furthermore, this mode is prone to breakdown and high discharge temperatures, easily leading to seed scorching.

1.3 Spark and Glow Discharge

Spark discharge is mechanistically distinct from other forms, characterized by high current requirements and accompanying flashes and cracking sounds in charged regions with high potential differences. Although the voltage between the poles is high during discharge, the power supply is limited; once discharge occurs, the channel resistance drops sharply, causing the voltage to fall and the discharge to interrupt temporarily. This results in an intermittent process. Thus, despite its high intensity, the discontinuity of spark discharge limits its application in continuous seed treatment.

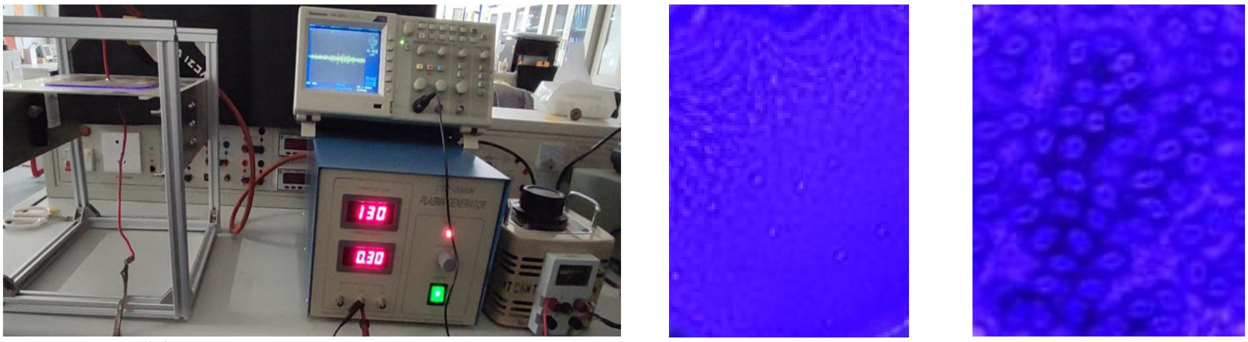
Glow discharge is a self-sustaining discharge phenomenon typically generated under low-pressure conditions (thin gas) and usually requires a sealed environment to maintain the plasma. Currently, this technology is mainly applied in the manufacturing of precision devices. However, in atmospheric, open-type agricultural scenarios, its applicability is limited due to the requirement for vacuum systems and the difficulty in achieving large-volume uniform discharge.

1.4 Dielectric Barrier Discharge (DBD) Seed Treatment

Based on the principle of Dielectric Barrier Discharge (DBD), a plate-to-plate seed treatment test bench was designed to investigate the discharge characteristics under different seed types and voltage parameters, as shown in Fig. 5(a) . The apparatus was primarily composed of a radio frequency (RF) power supply, a voltage regulator, an oscilloscope, and a seed treatment section. The discharge component of the test bench consisted of a high-voltage electrode and a grounded electrode. The dielectric barrier was constructed from quartz glass, while the high-voltage electrode plate was made of metal, and the frame was fabricated from aluminum alloy profiles.

The working principle of the Dielectric Barrier Discharge apparatus is described as follows: The height of the grounded electrode plate was adjusted via a screw rod. Seeds were spread flat on the grounded electrode, which was then elevated to an appropriate height. The high-voltage and grounded electrode plates were connected to the corresponding terminals of the power supply via wires. By regulating the voltage parameters of the power supply, the discharge phenomena of the device were observed and recorded.

Fig. 5 (b) and 5(c) illustrate the significant disparity in discharge phenomena with and without the presence of seeds under identical voltage conditions. It was observed that in the absence of seeds, atmospheric pressure DBD exhibited a filamentary discharge pattern. However, under the same conditions, the introduction of seeds caused the filamentary discharge to transition into a uniform discharge. The seed surfaces were uniformly wrapped by low-temperature plasma streamers, and the luminous intensity above the seeds was significantly higher than that in the interstitial regions. This indicates a dense distribution of low-temperature plasma over the seeds, whereas the regions between adjacent seeds exhibited weak luminescence and a lower plasma density. This phenomenon suggests that the introduction of seeds altered the electric field distribution between the plates and the transport behaviour of charged particles. This is likely due to the dielectric properties of the seed surface enhancing the local electric field, thereby promoting discharge uniformity and stability. Consequently, this result provides a critical basis for achieving continuous and uniform plasma treatment of seeds under atmospheric pressure.

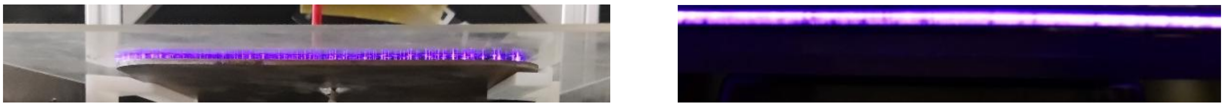


(a) DBD seed treatment test bench (b) Discharge phenomenon without seeds (c) Discharge phenomenon with seeds

Fig. 5 Dielectric barrier discharge seed treatment test bench

Medicago sativa (alfalfa) seeds were placed in the discharge test bench, and varying voltages (0–15 kV) were applied, resulting in the discharge phenomena shown in Fig. 6. As the discharge voltage was regulated and increased to 7 kV, discharge initiated at the locations of the seeds. With a further increase in voltage, the discharge intensity enhanced, the discharge area expanded, and discharge occurred in most of the air gap locations. As the voltage continued to rise, a large number of filamentary discharges began to appear in the air gap. When the voltage reached 10 kV, the alfalfa seeds were wrapped in low-temperature plasma. Upon the applied power supply voltage amplitude reaching 12 kV, the interior of the discharge device exhibited a complete and uniform discharge. Through these discharge tests, it was found that with the increase of discharge voltage, the Dielectric Barrier Discharge developed from filamentary discharge to uniform discharge. Under appropriate voltage conditions, DBD achieved uniform discharge, with low-temperature plasma wrapping the seeds, thereby subjecting them to uniform treatment.

(a) 7kV (b) 8kV

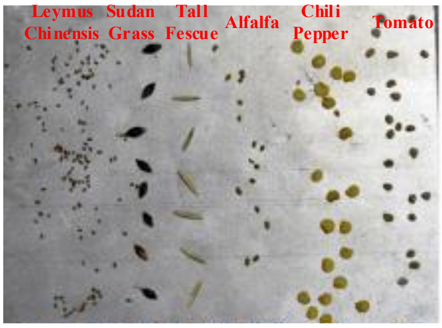


(c) 10kV (d) 12kV

Fig. 6 - Discharge phenomena of plasma treatment on alfalfa seeds under different voltages

To investigate the influence of seed physical characteristics on the dielectric barrier discharge process, various typical forage and crop seeds—including *Leymus chinensis*, Sudan grass, tall fescue, alfalfa, chili, and tomato—were selected. These were simultaneously placed within the same DBD electric field, and the power supply voltage was regulated within the range of 0–20 kV to systematically observe their discharge behaviour, as shown in Fig. 7. The results indicated distinct differences in the discharge inception voltage for different seeds within the same electric field.

As the voltage gradually increased, the locations occupied by the thicker alfalfa seeds were the first to induce discharge, followed sequentially by chili, tomato, and tall fescue seeds. When the voltage rose to 16 kV, all seeds were uniformly wrapped by plasma, and the electric field achieved complete and uniform discharge coverage. It was experimentally determined that seed thickness is negatively correlated with the required discharge voltage. The mechanism is inferred to be that an increase in seed thickness reduces the equivalent discharge gap between the seed surface and the upper electrode plate. This leads to a reduction in the number of initial electrons in the air gap of that region, which in turn lowers the reverse potential in the area above the seed (*Liu et al., 2023*). Therefore, under the same applied voltage, the actual electric field strength in the air gap surrounding thicker seeds is higher, making it easier to reach the discharge threshold and thereby preferentially inducing plasma discharge (*Judée and Dufour, 2020*). This phenomenon reveals the significant regulatory role of seed geometric characteristics in the DBD process.



(a) Different seed types

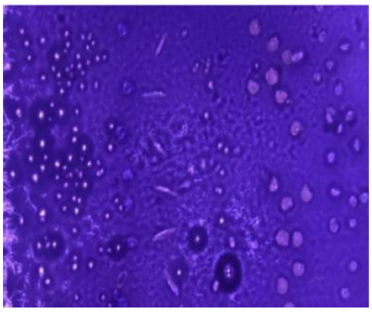

(b) Seeds fully wrapped by plasma

Fig. 7 - Discharge phenomena of different seed types in an electric field

As discussed in sections 1.1–1.3, the other discharge modes exhibit intrinsic limitations for continuous seed treatment. Corona discharge suffers from localized current concentration at the needle tip, leading to uneven charge distribution and a high risk of seed scorching (Fig. 4a–c).

Spark discharge is inherently intermittent due to its rapid breakdown and extinction cycle, making continuous uniform treatment unattainable. Despite reports demonstrating its efficacy in water sterilization and seed germination enhancement — for example, spark dielectric barrier discharge (SDBD) plasma achieved complete inactivation of E. coli and S. aureus after 8 min of treatment, increased coriander seed germination rate from 23.3% to 46.6% after 5 min, and reduced water contact angle from 105.65° to 57.19° owing to surface hydrophilization (*Dhakal et al., 2023*) — the intrinsic intermittency and discontinuity of spark discharge fundamentally preclude its application in continuous, large-scale seed processing. Gliding arc discharge, while capable of generating plasma at atmospheric pressure, produces a high-temperature arc zone that can thermally deform seeds and is further complicated by the tendency of small seeds to be dispersed by the required airflow (Fig. 2a–d, Fig. 3).

Glow discharge, though uniform and low in temperature, typically requires low-pressure (vacuum) conditions, which are impractical for large-scale, open-environment agricultural processing. Although large-volume atmospheric pressure glow discharge has been successfully demonstrated for Moringa oleifera seed treatment, achieving fungal disinfection and enhanced germination at low energy doses (2.46–4.35 mJ), it operates in a pulsed mode and still faces challenges in scaling to continuous seed flow (*Ouf et al., 2022*).

The requirement for precise gap control and the risk of arc transition at higher doses further limit its applicability for continuous, high-throughput processing. In contrast, Dielectric Barrier Discharge (DBD) overcomes all these drawbacks. Under the same atmospheric conditions, DBD generates a large-area, low-temperature, and remarkably uniform plasma. More importantly, the introduction of seeds into the DBD gap does not disrupt the discharge; instead, it promotes the transition from filamentary to uniform discharge (Fig. 5c), with the seeds being evenly wrapped by low-temperature plasma streamers (Fig. 6d, Fig. 7b). This unique behavior, attributed to the dielectric properties of the seed surface enhancing the local electric field (as described in section 1.4), enables continuous, non-thermal, and scalable treatment.

A systematic comparison of all five discharge modes based on experimental observations and literature evidence is provided in Table 1. Therefore, DBD is identified as the preferred discharge mode for developing continuous plasma seed treatment equipment for forage grasses under atmospheric pressure.

Table 1

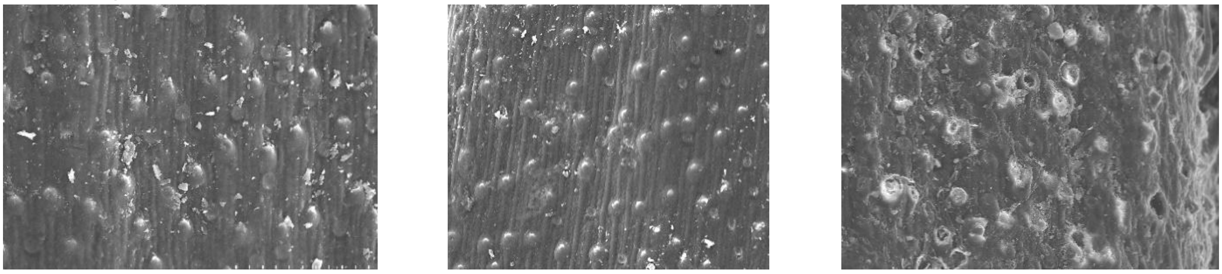
Comparison of different atmospheric pressure plasma generation modes

Discharge Mode	Uniformity & Continuity	Thermal Effect	Seed Damage Risk	Suitability for Continuous Treatment
Corona	Localized at needle tip (Fig. 4a–c)	Local temperature rise	Scorching at high voltage (Fig. 4d)	Low
Spark	Intermittent, flashes/cracking (*Dhakal et al., 2023*)	High (~1754 K)	Not directly observed	Very Low
Gliding Arc	Arc moves, small area (Fig. 2a–d)	High local temperature	Possible thermal deformation (Fig. 3)	Moderate
Glow	Uniform but requires low-pressure/vacuum; pulsed at atm. pressure (*Ouf et al., 2022*)	Low (~310 K)	Low at low doses, harmful at high doses	Low
DBD (This work)	Uniform, stable, large-area (Fig. 5c, 6d, 7b)	Room temperature, no charring	Controlled etching, no thermal damage (Fig. 8b, 9b)	**High**

2 Performance Evaluation Test Results

2.1 SEM Results and Analysis

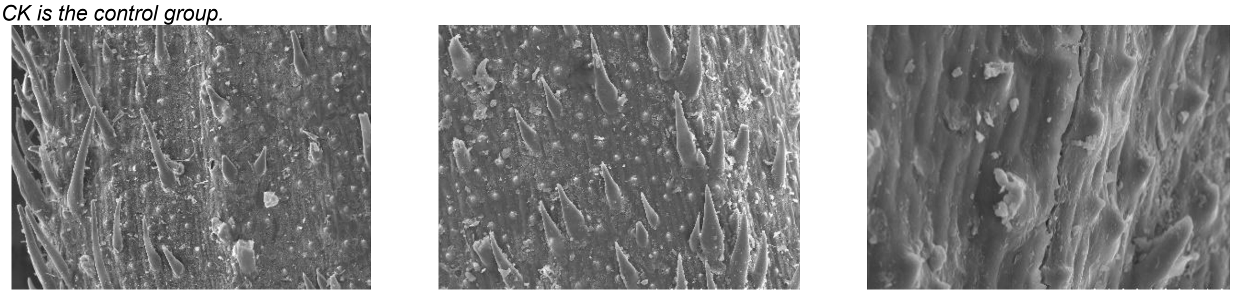
The constructed test bench was employed to conduct experiments for the treatment of *Leymus chinensis* seeds. To observe the microstructural changes of the seed coat following treatment at different voltages, Scanning Electron Microscopy (SEM) was utilized. A specific quantity of seeds was randomly selected from both untreated and treated batches, and the seeds were positioned in various orientations on the sample stage for observation.



（a）CK （b）10 kV （c）16 kV

Fig. 8 - Microstructural changes of *Leymus chinensis* seed coat before and after plasma treatment（×300）

Note: CK is the control group.



（a）CK （b）10 kV （c）16 kV

Fig. 9 - Microstructural changes of *Leymus chinensis* seed coat before and after plasma treatment（×500）

Note: CK is the control group.

Fig. 8 and 9 display the SEM micrographs of the *Leymus chinensis* seed coat surface under different treatment conditions. As shown in Fig. 8 (a) and Fig. 9(a), the surface of untreated seeds presented two typical morphologies: one side exhibited relatively uniform, smooth, granular protrusions, while the other side featured distinct long awn structures, with a certain amount of impurity contaminants attached to the surface. In contrast, the plasma-treated seeds, as shown in Fig. 8 (b-c) and Fig. 9 (b-c), exhibited significant surface modification. Distinct micropores and micro-cracks appeared on the surface. Furthermore, as the discharge voltage increased, surface contaminants were gradually reduced, pore sizes expanded, and the crack structures became more defined. This phenomenon is consistent with results reported in the literature (*Luchian et al., 2025*). The formation of these microstructures is conducive to enhancing the water absorption capacity of the seeds and promoting internal material exchange, thereby facilitating the breaking of seed dormancy.

These results further indicate that plasma treatment not only alters the seed coat structure through physical etching but may also indirectly regulate the physiological state of the seed by affecting the distribution of local active substances. The synergistic alteration of the aforementioned microstructure and composition provides direct evidence for explaining the plasma seed treatment mechanism regarding the enhancement of seed germination ability and stress resistance.

2.2 Analysis of the Effect of Plasma Treatment on Seed Electrical Conductivity

To comprehensively elucidate the mechanism of plasma treatment on seed physiology, quantitative verification was conducted using mechanistic data reflecting physiological functions, combined with the structural changes observed via SEM. The seed coat not only wraps and protects internal substances from external stress but also plays a key role in regulating material exchange between the embryo and the external environment. Changes in the structure and function of the seed coat can be indirectly reflected by variations in its permeability. Electrical conductivity serves as one of the indicators for evaluating seed vigor, as its value can sensitively reflect the integrity and permeability changes of the seed coat membrane system (*Araújo et al., 2022*). Seeds were placed in deionized water, and as the intracellular contents leaked out, the ion concentration of the leachate changed. This weak variation was quantitatively detected using a precision conductivity meter, providing critical data support for revealing the regulatory mechanism of plasma treatment on the seed physiological state.

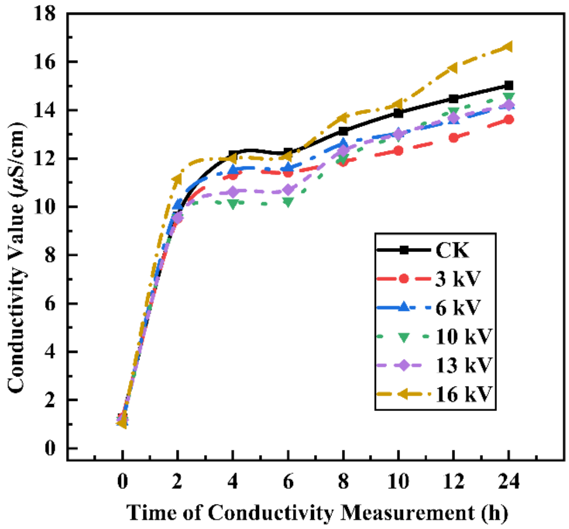


Fig. 10 - Changes in electrical conductivity of Leymus chinensis seeds before and after dielectric barrier discharge treatment

The measurement results of electrical conductivity revealed a distinct dosage effect of plasma treatment on *Leymus chinensis* seeds. As shown in Fig. 10, the conductivity data indicated a significant surge within 0 h to 2 h after immersion, primarily attributed to rapid water absorption by the awn structures of this gramineous seed. After 2 h, water absorption reached saturation and the conductivity change flattened.

Quantitative analysis of the 24 h conductivity values further elucidated the dosage effect. Compared to the control group (CK, 15.02 μS/cm), the 10 kV treatment reduced the final conductivity to 14.56 μS/cm, a decrease of approximately 3.1%, indicating enhanced membrane integrity and reduced ion leakage. In contrast, the 16 kV treatment increased the conductivity to 16.63 μS/cm, a 10.7% increase relative to CK, confirming that excessive energy input causes over-etching and loss of intracellular contents. This voltage-dependent biphasic response is consistent with previous reports on DBD treatment of wheat seeds (*Amado et al., 2025*) and alfalfa seeds (*Tang et al., 2015*), where moderate energy input improved surface wettability while excessive input led to over-etching. However, our findings extend these observations by directly correlating the conductivity surge with specific microstructural damage — notably, the formation of micropores and fissures at 16 kV (Fig. 8c, 9c) — which has not been quantitatively reported for gramineous forage seeds like *Leymus chinensis*.

Critically, unlike corona or gliding arc treatments reported for other species (*Xu et al., 2021*; *Liu et al., 2021*), the DBD configuration employed here enabled uniform treatment across the seed surface without localized overheating, as evidenced by the absence of charring or melting in SEM images. This confirms DBD's superior suitability for continuous, non-thermal processing of small-seeded forages.

In summary, Dielectric Barrier Discharge (DBD) plasma treatment can significantly alter the epidermal structure of *Leymus chinensis* seeds, but its effect is voltage-dependent; only an appropriate treatment voltage (e.g., 10–13 kV) can effectively enhance seed performance. These findings provide a quantitative basis for optimizing plasma treatment parameters in forage seed processing.

CONCLUSIONS

Through a systematic comparison and performance evaluation of different atmospheric pressure plasma generation modes, the efficacy of Dielectric Barrier Discharge (DBD) as the preferred technical path for continuous forage seed treatment was verified. The main conclusions obtained are as follows:

(1) Dielectric Barrier Discharge (DBD) was identified as the ideal generation mode for atmospheric pressure plasma. In contrast to the locality of corona discharge, the high temperature of gliding arc discharge, the intermittency of spark discharge, and the dependence of glow discharge on low-pressure environments, DBD is capable of generating large-area, uniform, and stable low-temperature plasma in atmospheric air. Consequently, it possesses superior adaptability for applications in plasma agriculture.

(2) The plate-type electrode configuration adopted by DBD facilitates integration into continuous conveying systems. This structure provides an ideal technical foundation for achieving large-scale, non-thermal damage treatment of forage seeds, thereby verifying the engineering feasibility of this technology for continuous agricultural production scenarios.

(3) The DBD plasma treatment exhibited a distinct dosage effect, and an optimal processing parameter window was identified. Experiments conducted on *Leymus chinensis* seeds demonstrated that treatment with appropriate parameters (e.g., 10–13 kV) induced surface modification, forming controllable micron-scale micropores and fissures on the glume surface, which effectively improved water and air permeability. Electrical conductivity kinetic analysis further confirmed at the physiological level that moderate treatment maintained cell membrane integrity while cleaning the surface. However, excessive energy input (e.g., 16 kV) led to excessive damage to the glume and the leakage of intracellular contents, thereby inhibiting seed vigor.

In conclusion, proceeding from principle verification and equipment realization to mechanism elucidation, this study systematically demonstrated the feasibility and application potential of atmospheric pressure DBD plasma treatment technology in overcoming germination obstacles in forage seeds. These findings provide a critical theoretical basis and design foundation for the development of green and efficient physical seed treatment equipment.

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