

Experimental investigation of corona discharge as a green technology for improving sorghum bicolor (L.) Moench seed germination

M. Bardadi Bendaha^{1,*}, Y. Benmimoun², B. Bekkouche¹, F. Kherbouche² and K. Miloudi³

¹Laboratory of Renewable Energies and Electrical Systems, Department of Electrical Engineering, University of Abdelhamid Ibn Badis, Mostaganem, 27000, Algeria

²Laboratory of Science and Technology of Water, Department of Electrical Engineering, University of Mustapha Stambouli, Mascara, 29000, Algeria

³Laboratory of Biological Systems and Geomatics Research, Department of Electrical Engineering, University of Mustapha Stambouli, Mascara, 29000, Algeria

*Correspondence: mourad.bardadibendaha@univ-mosta.dz

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Abstract. Sorghum bicolor (L.) Moench is a vital cereal crop widely cultivated in arid and semi-arid regions due to its notable drought tolerance and adaptability. Enhancing germination efficiency is crucial for improving crop establishment and overall productivity. This study explores the effects of negative DC corona discharge treatment (a non-thermal plasma-based seed priming method) on the germination. Sorghum seeds were exposed to voltages of 14, 18, 22, and 26 kV for durations of 5, 10, 15, and 20 minutes, with germination monitored over five days. After 24 hours, treatment at 22 kV for 15 minutes resulted in a 500% increase in germinated seeds compared to the control (18 vs. 3). By 48 hours, 18 kV for 15 minutes led to 40 germinated seeds versus 15 in the control group, marking a 166.7% improvement. The trend continued at 72 hours, with 44 seeds germinated under 22 kV for 15 minutes compared to 25 in untreated samples (76% increase). The 96-hour observation showed 44 germinated seeds at 22 kV for 5 minutes versus 28 in control (57.1% increase), while by 120 hours, 14 kV for 15 minutes produced 48 seeds compared to 32 in the control (50% increase). These results demonstrate that corona discharge treatment effectively accelerates early germination and enhances seed vigor, particularly under moderate voltage (14–22 kV) and exposure durations of 10–15 minutes, highlighting its potential as an eco-friendly strategy to boost sorghum crop performance.

Key words: corona discharge, germination enhancement, seed priming, sorghum bicolor, food security, sustainable agriculture.

INTRODUCTION

Sorghum is a vital cereal crop globally (Kibalnik et al., 2021), valued for both its adaptability and health-promoting properties. Whole grain sorghum is rich in bioactive compounds with significant health benefits, including antioxidant activity that supports

antimicrobial effects, reduces oxidative stress, and provides anti-inflammatory and anti-cancer properties (Vanamala et al., 2018; Xu et al., 2021; Morfin-Gutiérrez et al., 2025). These compounds are also known to exhibit anti-atherosclerotic and anti-tumorigenic activities, as well as potential for glycemic regulation (Stefoska-Needham et al., 2015). Agronomically, sorghum thrives in tropical and subtropical semi-arid regions, showing resilience in areas with limited rainfall and high temperatures due to its C4 photosynthetic pathway, which allows efficient carbon fixation and water use (Rashwan et al., 2021). As a short-day plant, sorghum shows excellent adaptability to hot, dry environments, making it a promising climate-resilient crop (Singh et al., 2024). Sorghum is primarily self-pollinating, though outcrossing can occur up to 6% depending on genotype and environmental conditions (Barnaud et al., 2008).

Seed germination and seedling establishment are fundamental for crop productivity, particularly under the pressures of climate variability and environmental degradation (Huliaieva et al., 2025). However, existing seed priming techniques, such as hydropriming and chemical treatments, often lack reproducibility and may pose environmental risks (Li et al., 2024; Khanahmadi et al., 2025). Consequently, sustainable and innovative methods like non-thermal plasma (NTP) and plasma-activated water (PAW) are gaining traction for enhancing seed performance without adverse environmental effects (Yan et al., 2022).

Initially, non-thermal plasma (NTP) is a partially ionized gas composed of reactive oxygen and nitrogen species (RONS) (Yan et al., 2024), ultraviolet (UV) light, and electromagnetic fields (Požėlienė et al., 2008; Pozeliene & Lynikiene, 2009), all of which induce physiological and biochemical changes in seeds. As illustrated in Fig. 1, NTP increases membrane permeability, accelerates water uptake, modulates phytohormones, and enhances antioxidant enzyme activity (Guragain et al., 2021; Yan et al., 2022). In radish seeds, DBD plasma using argon improved germination, pigment content, water absorption, and surface morphology, although prolonged exposure reduced seed vigor (Guragain et al., 2021). Similarly, Mohajer et al. (2024) demonstrated that DBD plasma combined with PAW improved cotton seedling growth by up to 76%, with improved hydrophilicity and metabolic activity.

Moreover, corona discharge plasma is widely used as an atmospheric-pressure plasma method, this technique yielded significant results across several crops. Nevertheless, its application in sorghum remains underexplored. Nucifera et al. (2016)

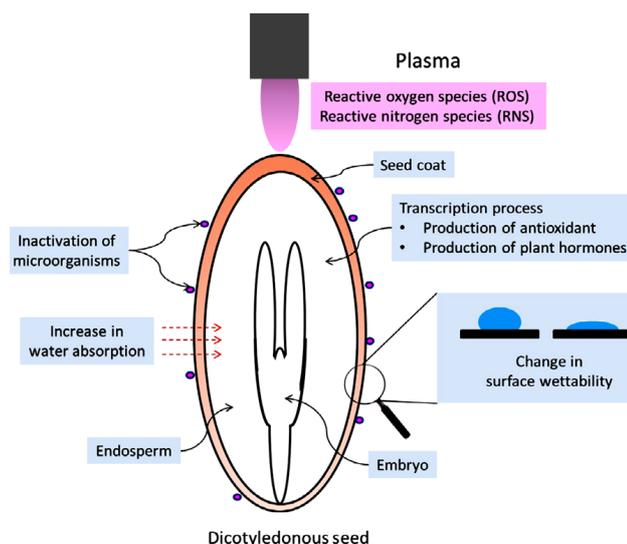


Figure 1. A pictorial summary of the mode of action of plasma on seeds, resulting in germination enhancement (Ohta, 2016).

reported a 314% increase in germination and substantial shoot elongation in black soybean. Ruangwong et al. (2020) showed that atmospheric corona discharge not only enhanced rice germination but also decontaminated fungal pathogens and extended seed shelf life. Lynikiene (2001) observed similar enhancements in carrot seeds, with corona-treated seeds showing better germination and higher quality separation. In broccoli, Kim et al. (2017) found that corona plasma reduced microbial contamination while improving sprout quality and maintaining sensory characteristics, but data on sorghum are limited or lacking detailed optimization of treatment parameters. Adhikari et al. (2020) reviewed how NTP and PTW inactivate pathogens while simultaneously activating plant immune responses through the expression of defense 'plasma vaccination', which refers to the ability of non-thermal plasma to stimulate a plant's natural defense mechanisms. When seeds or tissues are exposed to plasma-generated reactive species, UV light, and electric fields, these signals 'prime' the plant's immune system like a vaccine by activating stress and defense pathways.

In addition to atmospheric systems, low-pressure plasma systems have also been tested with positive outcomes. Hassan et al. (2019) treated *Bassella alba* seeds using radiofrequency plasma and reported significantly higher germination (60% vs. 36% in controls), increased plant height, and improved resilience in poor soil without pre-watering. Holonec et al. (2021) applied gamma radiation and electromagnetic fields to sessile oak seeds, observing increases in germination and seedling morphology, particularly under optimized exposure parameters. Khuzina et al. (2025) found that spring wheat seeds treated with corona discharge plasma at 8 kV and 0.5 kHz for 30 seconds showed maximum seedling length and vigor, suggesting dose and frequency are key.

Complementing direct plasma methods, the role of PAW has expanded due to its stability and scalability. Sajib et al. (2020) showed that PAW enhanced germination in black gram and increased catalase enzyme activity and gene expression. In barley, Seleiman et al. (2024) found that magnesium-neutralized PAW (Mg-PAW) promoted germination, increased chlorophyll and protein content, and reduced oxidative stress. Plasma-treated water was also effective in activating plant metabolic processes and enhancing root/shoot development (Mohajer et al., 2024).

To advance the understanding of the action mode, the theoretical basis for these treatments has also been developed. Kumar & Pandey (2021) proposed a causal theory linking high-voltage electric and magnetic fields to increased membrane permeability and ion flow, explaining faster germination near HVDC lines. Supporting this experimentally, Xu et al. (2019) showed in oats that corona-discharge-generated electric fields improved seed hydrophilicity and water absorption by etching seed coats and increasing conductivity.

Besides plasma and electric fields, other physical priming techniques have been studied. High-voltage electric fields (Xu et al., 2019), magnetic fields (Holonec et al., 2021), and ozone or UV treatments (Rifna et al., 2019) have shown effectiveness in improving seed vigor, few studies provide time-course germination data or identify optimal voltage-duration combinations tailored to sorghum. This represents a clear knowledge gap in the literature. Rifna et al. (2019) reviewed various non-thermal methods, highlighting PAW, pulsed electric fields (PEF), UV, ultrasound, and ozone as promising for dormancy release and improved biochemical traits. Meanwhile, chemical

priming remains relevant for stress conditions. Maaroufi-Dguimi et al. (2024) reported that 48-hour Ca (NO₃)₂ priming in tomato seeds under salt stress maintained 100% germination and significantly improved seedling metrics.

Furthermore, environmental factors such as temperature stress must be considered. Sari (2023) showed that sorghum germination peaked at 20–32 °C, with complete inhibition at 38 °C, emphasizing the need for seed treatments that enhance thermal tolerance. In line with this, plasma-based priming has demonstrated potential in maintaining vigor under adverse conditions (Hassan et al., 2019).

To address this, the present study investigates how corona discharge treatment at different voltages (14–26 kV) and durations (5–20 minutes) influences sorghum germination dynamics over 120 hours. By quantifying germination at early time points and comparing treatment combinations, this work aims to define optimal, scalable conditions for pre-sowing seed enhancement. The findings contribute to the development of practical, field-ready NTP applications and add novel insights specific to sorghum, a climate-resilient crop critical for food security.

MATERIALS AND METHODS

The application of non-thermal plasma (NTP), particularly corona discharge, in seed priming is theoretically grounded in its ability to generate reactive oxygen and nitrogen species (RONS), ultraviolet radiation, and transient electric fields. These agents interact with seed surfaces to induce biochemical and physiological changes such as increased membrane permeability, enhanced water absorption, phytohormone modulation, and activation of antioxidant enzymes (Guragain et al., 2021; Yan et al., 2024). These mechanisms support faster and more uniform germination. This study is guided by this framework, which provides the basis for investigating how specific voltage and exposure combinations affect germination in *Sorghum bicolor*.

Plant material

In this experiment, *Sorghum bicolor* (L.) Moench seed variety (Fig. 2) was selected for corona discharge treatment.

Native to Africa, it thrives in arid and semi-arid climates, making it a staple for over 300 million people, especially in Asia and Africa. This C4 plant is genetically diverse and exhibits strong adaptability due to its wide range of genotypes and phenotypic traits, which are vital for breeding and improving yield performance (Prasad & Sridhar, 2019). Sorghum's dual-purpose varieties offer both grain and fodder, making it a valuable resource for food, feed, and industrial products like biofuels (Meena et al., 2020) (Rodríguez et al., 2024). This seed variety is



Figure 2. Photography of *Sorghum bicolor* (L.) seeds.

a robust, fast-growing, C4 photosynthetic pathway cereal crop that ranks fifth among the world's major grains, following wheat, rice, maize, and barley. Under normal, sorghum seeds generally begin germinating within 24–48 hours after sowing, and full germination can be expected by day 3 to day 5, assuming ideal temperature and moisture levels.

Experimental bench for Sorghum seeds treatment

Fig. 3 provides a schematic of the experimental bench designed for sorghum seed treatment by corona discharge consists of five main components integrated into a compact and functional system.

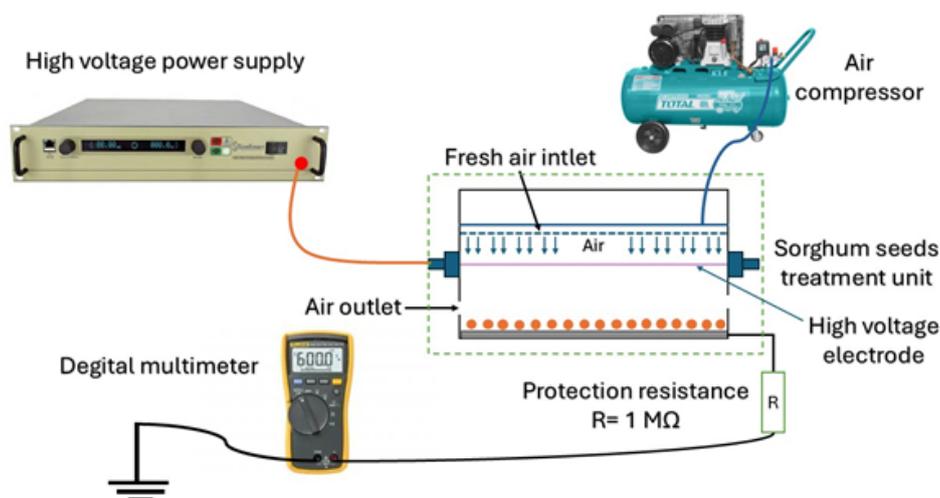


Figure 3. Schematic of the experimental bench designed for sorghum seed treatment.

The system is based on a negative high-voltage (-40 kV) DC supply, connected to an active electrode of wire 0.01 mm in diameter. This power supply generates an intense electric field between the high voltage electrode and a grounded electrode, spaced 5 cm apart, thus inducing the formation of a corona discharge.

The treatment chamber used in this experiment has dimensions of 30×30×25 cm (L×W×H). It is specifically designed for the treatment of sorghum seeds, ensuring uniform exposure to the ionized air. To enhance ionization and maintain a consistent treatment environment, a compressed air source supplied by an air compressor which introduces fresh air at a flow rate of 10 L min⁻¹ through an inlet system placed at the top of the chamber. This airflow aids in stabilizing the corona discharge and transporting reactive species across the seeds. The continuous exchange of air is ensured by the air outlet, located on the opposite side of the chamber. A digital multimeter is connected in series with a protection resistor of 1 MΩ, allowing accurate measurement of the discharge current while maintaining operator safety.

Seedling characteristics

Following treatment with the specified corona discharge parameters, a germination test was conducted on sorghum seed samples under controlled conditions (Mascara, Algeria: 22 °C, 45%–50% relative humidity). Each treatment group consisted of 50 seeds exposed to one of four high-voltage levels (14, 18, 22, or 26 kV) and one of four

exposure durations (5, 10, 15, or 20 minutes). An untreated control group of 50 seeds was included for comparison.

Seeds from all groups were placed on humidified cotton substrates in Petri dishes, with 10 seeds per dish and five replicates per treatment. All samples were incubated under identical environmental conditions. Germination was observed and recorded over a 5-day period, with counts taken at specific time points: 24, 48-, 72-, 96-, and 120-hours post-treatment. This time-course approach allowed assessment of both early and sustained germination responses.

RESULTS AND DISCUSSION

Corona discharge measurement

Fig. 4 illustrates the relationship between discharge current and power consumption as functions of applied negative DC voltage in a wire-to-plate configuration under controlled environmental conditions ($T = 23\text{ }^{\circ}\text{C}$, $\text{RH} = 44\%$). As the applied voltage increases from -10 kV to -30 kV , the discharge current shows a non-linear growth, starting from just above $2.4\text{ }\mu\text{A}$ and reaching over $140\text{ }\mu\text{A}$ at the maximum voltage. As expected, the discharge current increases progressively with the applied voltage once it surpasses the onset corona voltage. This behaviour is expected as higher electric field intensities enhance ionization once the onset voltage is exceeded.

Negative DC high voltage was selected for the experiment because, at any given voltage, the discharge current is significantly higher under negative polarity. This is primarily due to the greater apparent mobility of negative charge carriers compared to their positive counterparts, which enhances ionization efficiency and promotes more intense corona discharge (Kasdi et al., 2023; Kherbouche et al., 2016). The average current-voltage dependence can be described by a theoretical formula (Eq. 1) established for wire-to-plane configurations, confirming that the geometry plays a significant role in determining the corona discharge characteristics (Kherbouche et al., 2016).

$$I = CV(V - V_0) \quad (1)$$

where V_0 is the corona onset voltage and C is a constant that depends on the electrode configuration and the mobility of charge carriers, among other parameters.

In parallel with the increase in discharge current, Fig. 4 also shows a rise in power consumption, which follows an approximately quadratic trend with the applied voltage, reaching around 4.5 W at 30 kV . This power curve reflects the

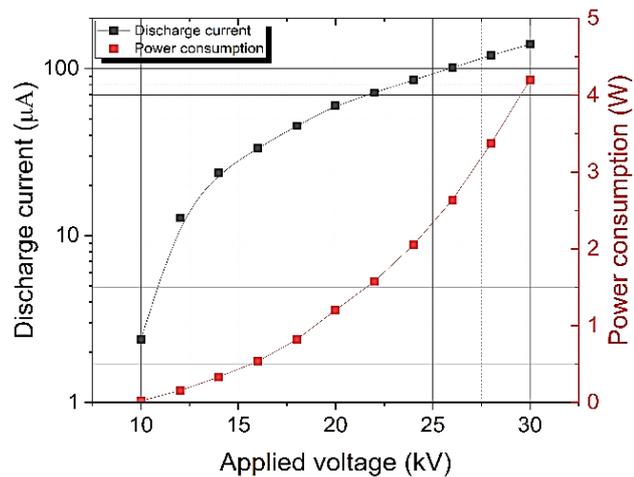


Figure 4. Current-voltage characteristics and power consumption for negative corona discharges in wire to plate configuration ($T = 23\text{ }^{\circ}\text{C}$, $\text{RH} = 45\%$).

combined effect of increasing voltage and current ($P = V \times I$), with energy losses primarily attributed to air ionization and its resistive properties. This behaviour is consistent with findings reported in (Kasdi et al., 2023), who observed similar non-linear I–V characteristics in DC corona systems and highlighted the influence of electrode gap and voltage on discharge stability (Kasdi et al., 2023). These results confirm that wire-to-plate corona configurations are effective for generating sufficient ion currents at manageable power levels, providing a promising pathway for non-thermal seed treatment applications.

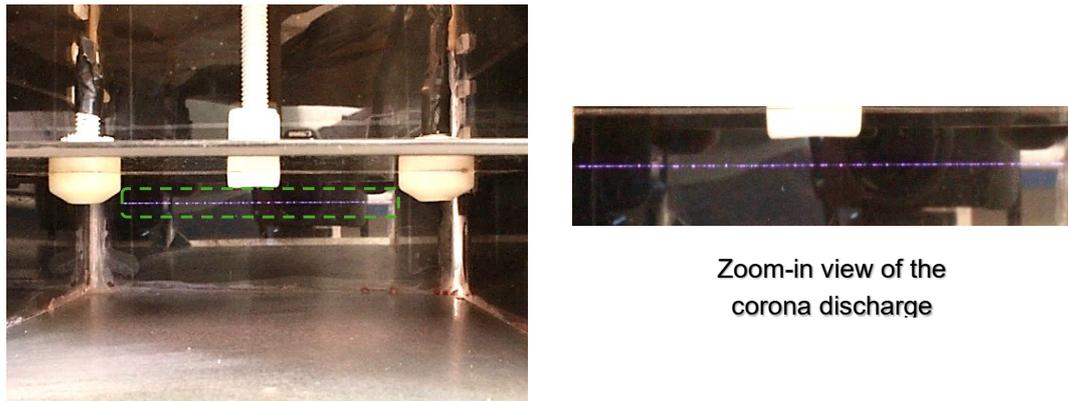


Figure 5. Morphology of positive and negative corona discharges. Experimental conditions: voltage = -26 kV, resolution = 5184 × 3456 pixels, exposure time = 10 s.

The morphology of negative corona discharge at applied voltages (-26 kV) close to breakdown is shown in Fig. 5, the negative DC corona exhibits discrete luminous region referred to as 'tufts' localized along the corona wire.

Effect of corona discharge and the treatment times on the Sorghum bicolor (L.) seeds germination

Corona discharge treatment significantly accelerated the early germination of Sorghum bicolor seeds, subfigures in Fig. 6 (a–e) demonstrate the impact of corona discharge treatment on the germination dynamics of sorghum seeds subjected to different negative DC voltages (14, 18, 22, and 26 kV) and exposure durations (5–20 minutes) during a 5-day observation period. At 24 hours (Fig. 6, a), early germination is significantly improved under specific treatment conditions, notably at 22 kV for 15 minutes, where 18 seeds germinated compared to only 3 in the control group. This represents a substantial enhancement in germination, amounting to a 500% increase under the specified corona treatment condition. This level of improvement far exceeds the 314% increase reported by Nucifera et al. (2016) under similar electric field conditions.

Fig. 6, (b) illustrates the number of germinated sorghum seeds at 48 hours, the most effective treatment was observed at 18 kV for 15 minutes, yielding approximately 40 germinated seeds, while the control group showed only 15, corresponding to an increase of around 166.7%. After 72 hours [Fig. 6, (c)], the seeds sample treated at 22 kV for 15 minutes produced the maximum germination of 44 seeds, while the control reached approximately 25 seeds, indicating a 76% improvement.

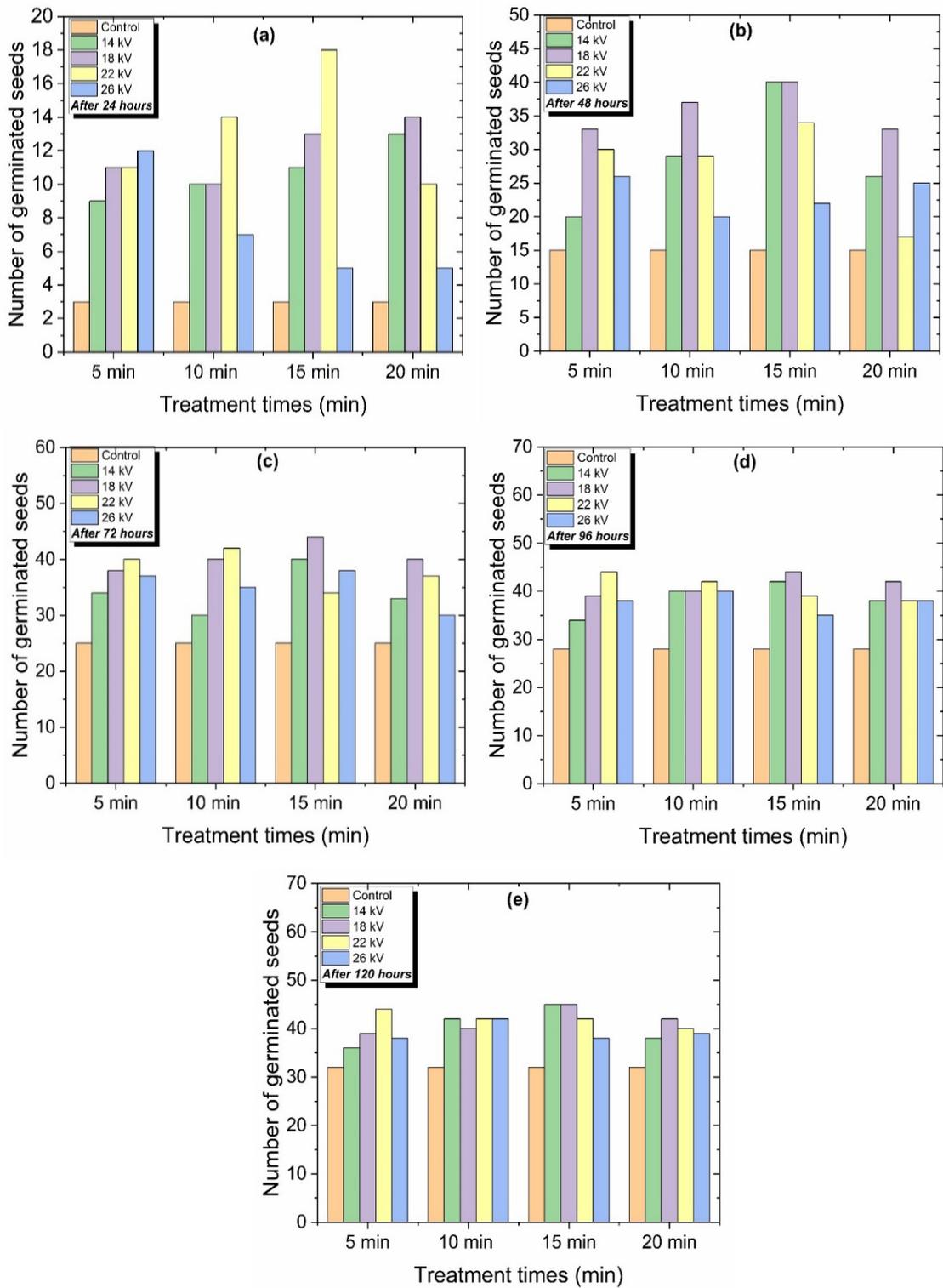


Figure 6, (a–e). Effect of Corona Discharge Treatment on Sorghum Seed Germination at Different Negative DC Voltages and Exposure Times Over a 5-Day Period.

At 96 hours (Fig. 6, d), the highest count was 44 seeds at 22 kV for 5 minutes, versus 28 seeds in the control group, an increase of about 57.1%. Finally, at 120 hours (Fig. 6, e), the most effective treatment was 14 kV for 15 minutes, yielding 48 seeds, compared to 32 seeds in the control, representing a 50% increase. These results confirm that corona discharge treatment, especially at moderate voltages and exposure durations, significantly accelerates early germination and sustains a consistent improvement in germination performance over time.

By 96 and 120 hours (Fig. d, e), the germination counts across all treatments including the control samples begin to converge, suggesting that corona discharge primarily affects the timing rather than the ultimate extent of germination. This implies that the pre-treatment alters early physiological responses such as water uptake and metabolic activation, allowing treated seeds to initiate germination faster. Optimal conditions for acceleration appear to be between 18–22 kV and 10–15 minutes of exposure. These findings are consistent with previous studies on corona discharge in seed priming applications (Xu et al., 2021).

The early advantage suggests that the treatment accelerates physiological processes such as water uptake and metabolic activation without necessarily increasing the final germination percentage. By 96 and 120 hours, germination rates across all groups began to converge, indicating that corona discharge primarily affects the timing rather than the total extent of germination.

These results are consistent with findings in the literature on other crops, where plasma or electric field treatments also led to faster germination and enhanced seedling vigor. Similar trends have been observed in black soybean, rice, and oats, reinforcing the effectiveness of corona discharge as a non-chemical, scalable priming method. The results support the use of this technique as a promising solution for improving seed performance, particularly in regions where rapid and uniform germination is critical under climate-stressed conditions.

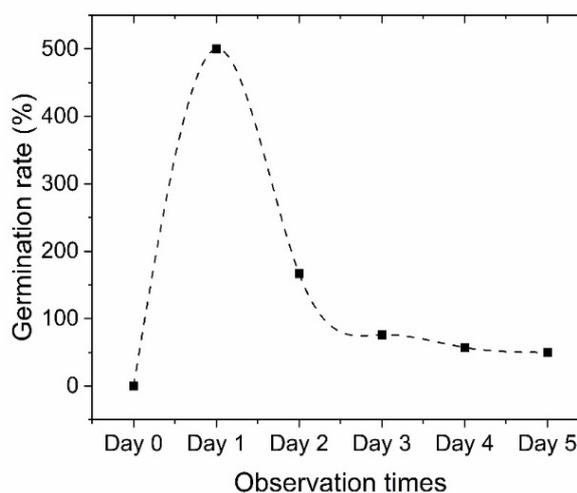


Figure 7. Sorghum Seed Germination dynamism.

Fig. 7 shows the germination rate over time (0–5 days), illustrating that treated seeds germinate more rapidly than controls. The curve represents the maximum germination rate values obtained from different corona discharge treatment conditions applied during the experiment.

Germination dynamism induced by corona discharge indicates that the treated seeds germinate much earlier than untreated seeds, also explains the convergence in germination performance over time.

The overall outcome indicates that the pre-treatment alters early physiological responses, allowing treated seeds to initiate germination faster. Optimal conditions for acceleration appear to be between 18–22 kV and 10–15 minutes of exposure. The accelerated germination may be attributed to increased membrane permeability, improved water uptake, and metabolic activation triggered by corona-induced plasma effects. These physiological enhancements support faster initiation of germination and early seedling development. These findings are consistent with previous studies on corona discharge in seed priming applications (Xu et al., 2021).

Effect of corona discharge treatment on early plant growth

Fig. 8 presents a visual comparison of seedling growth under different voltage treatments. Treated seedlings, particularly those exposed to 14 kV (42.9 mm) and 18 kV (46.1 mm), exhibited visibly longer shoots and more developed root systems compared to the control (22.4 mm). In contrast, the control sample showed limited shoot elongation and weaker root formation, indicating slower germination and lower initial vigor. These visual observations align with the quantitative germination data, confirming the beneficial impact of corona discharge on early plant growth and seedling development.

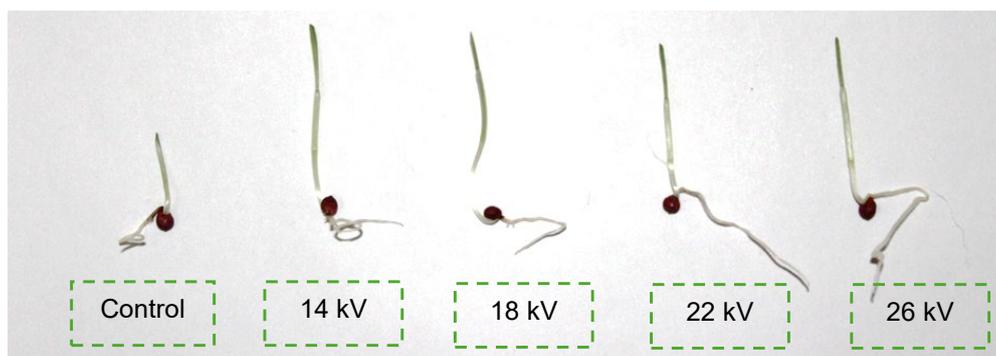


Figure 8. Growth response of sorghum seedlings under varying voltage treatments (day 6).

These findings highlight corona discharge as a sustainable and effective non-chemical seed priming method for improving early germination in sorghum. The technology offers advantages in speed, energy efficiency, and scalability. It may be especially useful in semi-arid regions where rapid germination can improve crop establishment under climate stress. Incorporating corona discharge priming into seed treatment protocols could support more resilient and productive agricultural systems, particularly in low-input farming contexts.

Policy Implications and Practical Applications

The results of this study indicate that corona discharge plasma treatment is a viable, non-chemical method for enhancing the germination of *Sorghum bicolor*, particularly under early growth conditions. This approach demonstrates rapid germination enhancement up to 500% under optimal parameters which can be especially valuable in arid and semi-arid regions where early seedling establishment is critical for crop survival. The plasma treatment's low energy requirements, chemical-free nature, and scalability make it an attractive component of sustainable agricultural development.

This method aligns with global efforts to reduce the environmental impact of agriculture by minimizing synthetic chemical use while improving crop productivity (Li et al., 2024; Khanahmadi et al., 2025). Previous studies have emphasized the potential of plasma technologies to enhance germination while also extending shelf life, reducing microbial contamination, and improving seedling vigor across various species (Kim et al., 2017; Mohajer et al., 2024; Ruangwong et al., 2020).

From a policy perspective, integrating corona discharge seed priming into national seed enhancement programs or public-private seed supply chains could offer a cost-effective, environmentally responsible alternative to chemical seed treatments. This would be especially impactful for crops like sorghum, which play a key role in food security for populations in drought-prone areas (Singh et al., 2024). Adoption of such technology would benefit from capacity building, technology standardization, and investment in local manufacturing of plasma equipment.

CONCLUSIONS

Corona discharge treatment has been demonstrated as an effective and energy-efficient method for enhancing the germination performance of Sorghum bicolor seeds. The findings reveal both the electrical behaviour of the system and its biological impact on seed behaviour. The main conclusions are summarized as follows:

- The discharge current in the wire-to-plate corona system increased non-linearly with applied negative DC voltage, reaching over 140 μA at -30 kV , with consistently higher discharge efficiency observed under negative polarity due to greater charge carrier mobility.
- The negative DC corona exhibits discrete luminous region referred to as 'tufts' localized along the corona wire, indicating strong surface ionization and discharge activity at the surface of the active HV wire.
- The system operated at low power levels, with energy consumption remaining below 5 watts even for 30 kV, making it an energy-efficient technique for seed priming.
- Corona discharge treatment significantly accelerated the early germination of sorghum seeds, with the most notable effect observed at 22 kV for 15 minutes, resulting in a 500% increase in germination at 24 hours compared to the control.
- The germination rates across all treatments began to converge by 96 and 120 hours, suggesting the treatment's effect is strongest during early development stages.
- The impact seems to be dose-dependent, since extremely high voltages (26 kV) and prolonged exposure durations showed diminishing or inhibitory effects on germination ability.
- The treated samples exhibited longer coleoptiles and more developed root systems than the control ones, indicating that corona discharge treatment not only accelerates germination but also positively influences early plant growth and development.

These results confirm that corona discharge is particularly effective in promoting rapid, early-stage germination, especially within the first 48 hours after sowing. The optimal performance was observed between 18–22 kV and 10–15 minutes of exposure. The method offers a sustainable, chemical-free approach to improve seed vigor, uniformity, and early crop establishment.

Future investigations should focus on large-scale field validation to assess the agronomic effectiveness of corona discharge treatment under variable environmental conditions. In addition, long-term studies are needed to evaluate its impact on full crop development and yield performance. Elucidating the underlying molecular and physiological mechanisms triggered by plasma exposure will also be essential to understand the biological basis of the observed effects. Furthermore, extending this approach to other climate-resilient crop species may broaden its applicability and contribute to the development of sustainable and resource-efficient agricultural systems.

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