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Research article

Exploring the effects of non-thermal plasma pre-treatment on coriander (*Coriander sativum* L.) seed germination efficiency

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ABSTRACT

This study investigates the effects of non-thermal plasma (NTP) treatment on the germination characteristics of coriander seeds (*Coriandrum sativum* L.). Different germination factors, water imbibition rate and changes in mass, were analyzed. The results indicate that a suitable duration of NTP treatment (180 s and 300 s) enhances seed germination characteristics, whereas prolonged exposure (420 s) leads to adverse effects. Furthermore, shorter NTP exposures (180 s) improved water absorption and surface properties of seeds, while longer exposures (420 s) caused mass loss and compromised seed vigor. Overall, the findings demonstrate the significance of optimizing NTP treatment conditions for enhancing seed germination characteristics.

1. Introduction

Seed germination and plant growth are crucial stages in the life cycle of plants, significantly impacting ecosystem establishment and productivity. Over the years, researchers have examined multiple factors that can influence the germination and growth of seeds, including light, temperature, moisture, and nutrient availability [1,2]. However, advancements in plasma science have recently revealed a new potential element that may impact plant development: non-thermal plasma (NTP). NTP technology offers a promising avenue for sustainable and eco-friendly advancements in agriculture, making it an important area of research and development [3–5]. The distinct characteristics of NTP, including the generation of reactive oxygen and nitrogen species (RONS), ultraviolet radiation, and electric fields, establish it as a promising resource for agricultural and horticultural applications [6–8]. NTPs potential to enhance pathogen control, seed germination, pest management, weed control, soil improvement, and food safety establishes it as a crucial domain for the agricultural sector's sustainable and environmentally friendly progress [9–12].

The outcomes of seed germination and growth when exposed to NTP can differ based on multiple factors such as the duration of treatment, the composition of gases utilized, the power of the discharge, and the specific responses exhibited by different plant species [10,13–15]. Several research studies have provided evidence of the beneficial impacts of NTP on various aspects of seed germination, including the rate, percentage, and consistency of germination [12,16,17]. Furthermore, the application of plasma treatment has been shown to improve the development of roots and shoots, increase the content of chlorophyll, enhance the activities of antioxidant

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enzymes, and promote overall plant growth [18–21]. However, the mechanisms underlying these effects remain largely unexplored, presenting a compelling opportunity for further research. Fan et al. observed that NTP treatment enhances melon seed germination, increases seed vigor, stimulates root growth, and reduces pathogenic microorganisms on seed surfaces [22]. Similarly, Mishra et al. observed that extended treatment time using the gliding arc on coriander seeds leads to increased seed temperature, decreased seed weight, and enhanced hydrophilicity in coriander seeds, with significantly longer roots and shoots observed in seeds treated for ten and 8 min, respectively [23]. Similarly, Florescu et al. observed that NTP treatment of sunflower seeds for 10 min in a dielectric barrier discharge (DBD) reactor operating in air, resulted in improved early growth, taller seedlings, greater total mass, increased capitulum size, and a remarkable increase in crop yield compared to the control samples [24]. In a study conducted by Ji et al. it was discovered that both N2 micro DBD plasma treatment and plasma-generated nitric oxide (PGNO) can improve the germination and seedling development of coriander seeds, with the electrical discharge energy and PGNO concentration being important factors in promoting these processes [25].

Coriander sativum seeds, a herbaceous plant with a low germination rate, are small and aromatic, valued for their culinary uses, medicinal properties, and nutritional benefits, adding flavor and potential health-promoting effects to various dishes [26]. This study sought to evaluate the effects of a cost-effective cold plasma treatment, generated by a custom designed 50 Hz plasma generator, on *Coriander sativum* L. seeds, along with its impact on growth-related features. The primary objective was to elucidate the mechanisms of NTP action on coriander seeds, with the ultimate aim of informing and planning for subsequent field experiments.

2. Methods

2.1. Experimental setup

The experimental arrangement comprises a reactor equipped with two circular copper electrodes, each measuring 5 cm × 0.8 cm, employed for treating coriander seeds [Fig. 1 a]. A 2 mm diameter borosilicate - glass was employed as the dielectric barrier, serving to provide electrical insulation, control the electric field for uniform plasma generation, and protect the electrodes during seed treatment.

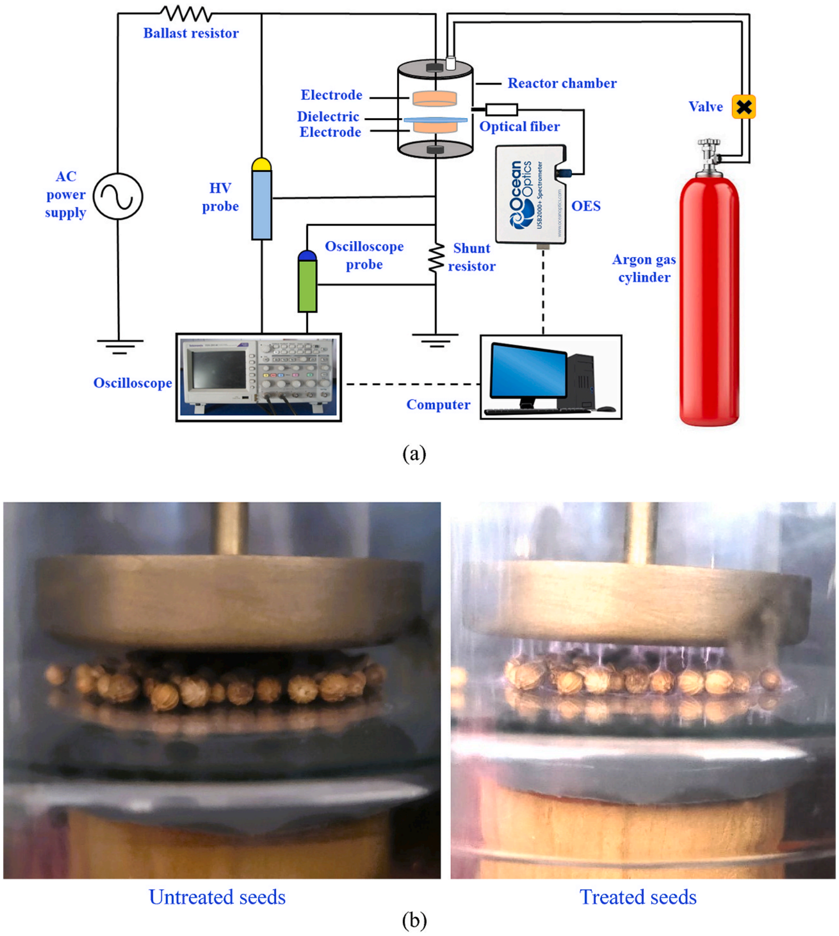

Fig. 1. (a) Schematic of the reactor system used for the treatment of seeds. (b) Images of the seeds and the discharge.

A discharge [Fig. 1b] was generated in an atmospheric pressure condition using a specially fabricated plasma driver operating at 11 kV r.m.s and 50 Hz, with argon as the carrier gas at a flow rate (Q) of 5 L/min. To maintain discharge stability, the argon flow rate inside the reactor was regulated with the assistance of a gas flow regulator (Yamato Scientific, Japan). The voltage across the electrodes was measured with the Pintek HVP-28HF high voltage probe (Pintek Electronics Co., Ltd, Taiwan), capable of sensing voltages up to 28 kV with an attenuation ratio of 1000:1. For current measurement, an oscilloscope probe (Kenwood PC-53 50 MHz Attenuator, Japan) was connected across a 10 kΩ shunt resistor. Both voltage and current signals were observed and recorded using a Tektronix TDS 2014C oscilloscope (Tektronix, Inc., USA). Similarly, the analysis of reactive species within the discharge was conducted utilizing the USB 2000+ spectrometer (Ocean Optics, Florida, USA). The spectrometer, featuring a 25 μm slit size, a grating with 800 lines/mm, an optical resolution of 0.3 nm, and a wavelength range spanning from 200 to 1100 nm, was utilized to identify the reactive species present in the discharge. The investigation entailed subjecting 250 dry coriander seeds to NTP at a 5 mm air spacing between electrodes for treatment durations of 180 s, 300 s, and 420 s. Each of these conditions was replicated three times.

2.2. Seed origin and treatment

Coriander seeds were obtained from 'Rajhdhani Agro Concern, Kathmandu, Nepal'. Only seeds that showed no visible defects were selected for the study. In the context of the present experimental investigation, a total of 250 coriander (*Coriandrum sativum*) seeds were strategically positioned immediately above the dielectric surface within the active discharge region of a NTP discharge apparatus. Methodical control over experimental conditions was maintained, with precise specifications including an RMS (Root Mean Square) voltage of 11 kV, a plasma frequency of 50 Hz, argon (flow rate, $Q = 5$ L/min), and a power input of 10 W, all of which were applied under atmospheric pressure conditions. The coriander seeds were exposed to NTP discharge for varying durations, spanning from 180 s to 420 s. To accurately monitor thermal dynamics, an infrared thermometer was employed, yielding a recorded discharge temperature of approximately 24 °C. It is of note that these experimental trials were conducted approximately 24 h subsequent to the initial NTP treatment. Upon completion of the plasma exposure, the treated coriander seeds were expeditiously transferred and stored within sterile grip-sealed polypropylene bags. The cocopeat substrate, a critical component of this study, was subjected to a meticulous preparatory process involving thorough washing with distilled water, followed by subsequent drying at ambient temperature conditions. Subsequently, the desiccated cocopeat was uniformly blended with vermicompost, serving as the foundational medium for the germination trays. These germination trays accommodated both untreated control seeds and the treated seeds, thereby facilitating a controlled and comparative analysis. To ensure consistent and optimal moisture levels conducive to germination, uniform quantities of distilled water were systematically introduced to all trays at 24-h intervals. The plants were cultivated in a regulated environment, maintaining a temperature of 26 °C during the light period and 18 °C in the dark. The cultivation followed a 12-h light/12-h dark cycle, with a photon flux density of 100 μmol/m^2/s. Additionally, a relative humidity range of 60–70% was maintained. The criteria for successful germination were established as the emergence of radicals reaching a minimum length equivalent to half of the seed length. Over a span of 15 days, the percentage of germination was meticulously recorded at daily intervals. Upon the conclusion of this predetermined germination period, meticulous measurements were conducted to quantify seedling lengths.

The comprehensive evaluation of seed germination encompassed a thorough analysis, involving a spectrum of parameters [Equations (1)–(11)]. These parameters encompasses estimating germination percentage, mean germination time, coefficient of variation of germination time, coefficient of velocity of germination, germination index, uncertainty of the germination process, synchronization index, mean daily germination, germination value, vigor index, mass loss, imbibition rate, and water contact angles in accordance with established methodologies by eminent researchers [12,21,27–30]. The experimental design employed a well-structured approach, adopting a completely randomized design with three independent replications.

$$\text{Germination percentage (GP)} = \frac{\sum_{k=1}^{15} n_k}{N} \times 100 \tag{1}$$

Here, n_k = number of seeds germinated during the kth time and N = total number of seeds utilized

$$\text{Mean germination time, MGT}(\bar{t}) = \frac{\sum_{k=1}^{15} n_k t_k}{\sum_{k=1}^{1} n_k} \tag{2}$$

$$\text{Coefficient of variation of germination time } (CV_t) = \frac{\sqrt{\frac{\sum_{k=1}^{15} n_k (t_k - \bar{t})^2}{\sum_{k=1}^{15} (n_k - 1)}}}{\bar{t}} \times 100 \tag{3}$$

$$\text{Coefficient of velocity of germination (CVG)} = \frac{\sum_{k=1}^{15} n_k}{\sum_{k=1}^{15} n_k t_k} \times 100 \tag{4}$$

Here, $n_k t_k$ = number of seeds germinated at an k^{th} time interval

$$\text{Germination index (GI)} = \frac{\sum_{k=1}^{15} n_k}{t_k} \tag{5}$$

Here, t_k = time taken for seeds to germinate at k^{th} time

$$\text{Uncertainty of germination (U)} = \sum_{k=1}^{15} f_k \log_2 f_k \tag{6}$$

Here, $f_k = \frac{n_k}{\sum_{k=1}^{15} n_k}$, Where; f_k is the relative frequency of germination.

$$\text{Synchronization Index (Z)} = \frac{\sum_{k=1}^{15} C_{n_{k,2}} t_k}{C_{\sum n_{k,2}}} \tag{7}$$

$$; C_{n_{k,2}} = \frac{n_k(n_k - 1)}{2}$$

Where; $C_{n_{k,2}}$ = combination of seeds germinated in the k^{th} time, and n_k is the number of seed germinated on k^{th} time.

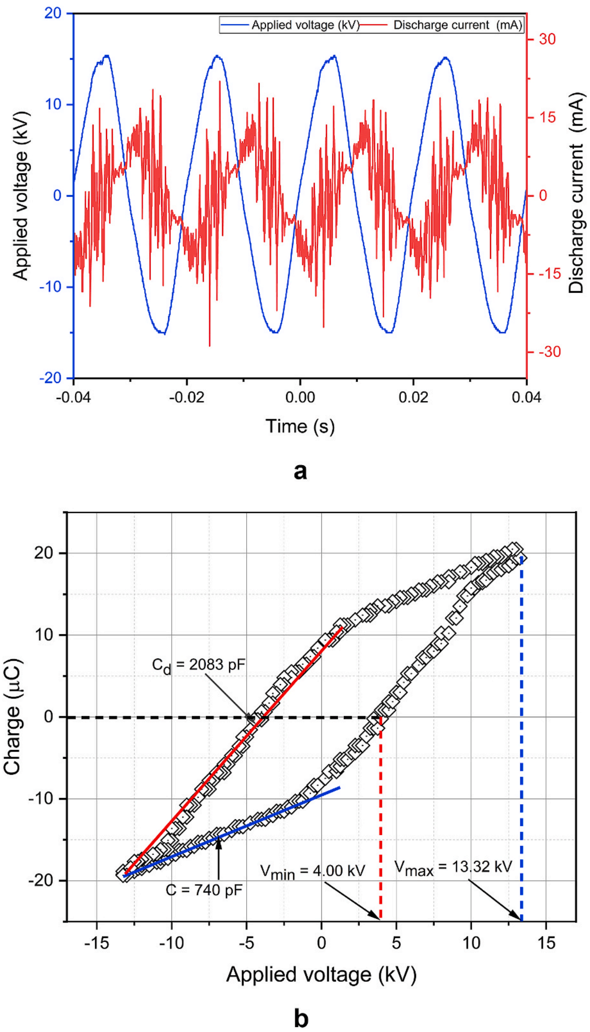

Fig. 2. (a) Waveform of discharge current and applied voltage with time. (b) Q(t)-V(t) plot of NTP discharge.

$$\text{Mean daily germination (MDG)} = \frac{\text{Final cumulative germination (\%)}}{\text{Total number of intervals required for germination}} \tag{8}$$

$$\text{Peak value (PV)} = \text{maximum}\left[\frac{G_1}{T_1}, \frac{G_2}{T_2}, \text{........}, \frac{G_k}{T_k}\right] \tag{9}$$

Here, T_j signifies the duration from the commencement of the investigation to the jth interval, G_j represents the overall percentage of germination during the jth time span, and k indicates the total count of time intervals.

$$\text{Germination value (GV)} = \text{MDG} \times \text{PV} \tag{10}$$

$$\text{Time to 50 \% of seed germination } T_{50} = \frac{t_k + \left(\frac{\sum_{k=1}^{l=15} n_i}{2} - n_k\right)}{n_l - n_k}(t_l - t_k) \tag{11}$$

Where, n_k and n_l = nearest cumulative number of seeds germinated $C_{n_k} < \frac{\sum_{k=1}^{l=15} n_k}{2}$ and $C_{n_l} > \frac{\sum_{k=1}^{l=15} n_k}{2}$ respectively.

t_k and t_l = the time span that corresponds to n_k and n_l respectively.

2.3. Statistical analyses

The mean ± standard deviation was utilized to depict the results derived from three replicated experiments. To examine significant variations in mean germination parameters, a one-way ANOVA was utilized, followed by Tukey's multiple comparison tests. The statistical significance at $p < 0.05$ was denoted by assigning distinct letters (a-d) to the corresponding values.

3. Results and discussion

3.1. Electrical characterization of the discharge

Fig. 2a depicts the waveform of the applied voltage and the corresponding discharge current, obtained from a custom-designed high voltage (11 kV rms, 50 Hz) ac power source. The experiment reveals the occurrence of multiple filamentary streamer-based micro-discharge patterns within a single sine voltage pulse. The identification of these filamentary streamer-based micro-discharges serves as a distinctive feature of DBD.

The estimation of power (P) was carried out by plotting the charge and the voltage waveform [Fig. 2b], and then analyzing the data accordingly using Equation (12) [31].

$$P = 4f\, C_d \frac{V_{min}(V_{max} - V_{min})}{1 + \frac{C_g}{C_d}} \tag{12}$$

In our current research, the parameters f, V_{max}, and V_{min} represent the input signal frequency (50 Hz), maximum (13.32 kV), and minimum (4.00 kV) input voltage required to initiate the discharge, respectively. Additionally, C_d and C_g refer to the capacitance of the

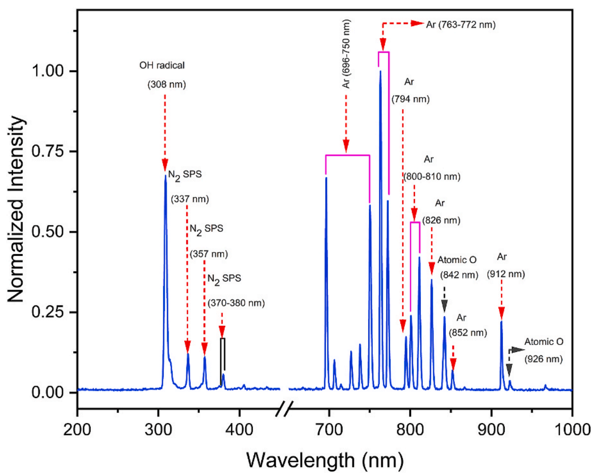

Fig. 3. Emission spectrum of the Ar discharge in an ambient air.

dielectric and the gas, respectively. At an applied voltage of 11 kV rms, the power consumption (P) was measured to be 10 W. Notably, the introduction of seeds into the air gap caused a noticeable change in the power consumption.

3.2. Optical signal analysis

Fig. 3 illustrates the spectrum of the discharge generated in an argon environment with a flow rate of 5 L/min and at an applied voltage of 11 kV rms and 50 Hz frequency. The spectrum exhibits prominent peaks corresponding to various argon species with higher intensities. Notably, the existence of the hydroxyl radical (308 nm), N_2 second positive system at various wavelengths (337 nm, 357 nm, 370 nm, 380 nm), atomic oxygen (777 nm, 842 nm, and 926 nm), and excited argon atoms are evident from the spectrum's intensity regions. The significant existence of RONS in the spectrum suggests the likelihood of chemical reactions occurring within the system. This could lead to the formation and accumulation of reactive species, which may potentially influence the seed [18,19].

For the estimation of excitation temperature (T_{exc}), suitable lines of Ar I (at wavelengths 675.28 nm, 687.12 nm, 703.02 nm, 706.72 nm, and 750.38 nm) were utilized from the emission spectrum to determine the excitation temperature using the Boltzmann plot method [32]. The wavelengths (λ) and intensities (I) of these spectral lines were obtained from spectrum [Fig. 3] The crucial parameters: statistical weight values (g), transition probabilities (A), and energy levels (E_j) for these four chosen lines in Equation (13) were obtained from "The National Institute of Standards and Technology (NIST) Atomic Spectra Database" [33].

$$Ln\left(\frac{I\lambda}{Ag}\right) = -\frac{E_j}{KT_{exc}} + C \tag{13}$$

Here, the K is the Boltzmann constant and C is a constant.

By plotting energy along the horizontal-axis and $Ln\left(\frac{I\lambda}{Ag}\right)$ along the vertical-axis, a linear relationship was achieved [Fig. 4]. The slope of this linear plot enabled the calculation of the T_{exc}. As depicted in Fig. 4, the calculated T_{exc} was 0.68 eV. The linear fitting exhibited a high level of consistency with an R-square value of nearly 0.91, affirming the satisfactory validation of excitation equilibrium within the NTP discharge. This determination of excitation temperature enabled us to confirm that the energy needed for the creation of radicals and ions in the discharge was provided by the free electrons.

3.3. Germination parameters

Over a span of 15 consecutive days, a comprehensive and methodical record was diligently maintained, documenting the unfolding process of seed germination on a daily basis. The study incorporated three replicates, with each treatment group comprising 250 coriander seeds, to enhance the robustness and reliability of the observed germination patterns. This meticulous record-keeping was augmented by a thorough analysis of an array of parameters closely associated with the germination phenomenon. This research endeavor aimed to unravel the intricate details of how seeds embark on their developmental journey and to glean insights into the factors influencing this crucial biological process.

Coriander seeds were subjected to NTP treatment for durations of 180 s, 300 s, and 420 s. Our results revealed that the germination percentage (GP) of seeds for 180 s and 300 s increased by 41.7% and 12.6%, respectively, in comparison to control seeds. Conversely, seeds treated by NTP for 420 s displayed a decrease in germination percentage by 16.3% in comparison to control [Table 1]. The observed increase in GP of seeds treated with NTP for an appropriate duration (180 s, and 300 s) is likely due to the beneficial effects of the treatment on seed physiology and dormancy breakage, as NTP generates RONS, ultraviolet radiation, and electric fields that influence seed characteristics, resulting in dormancy breakage, improved seed coat permeability, and activation of germination-related

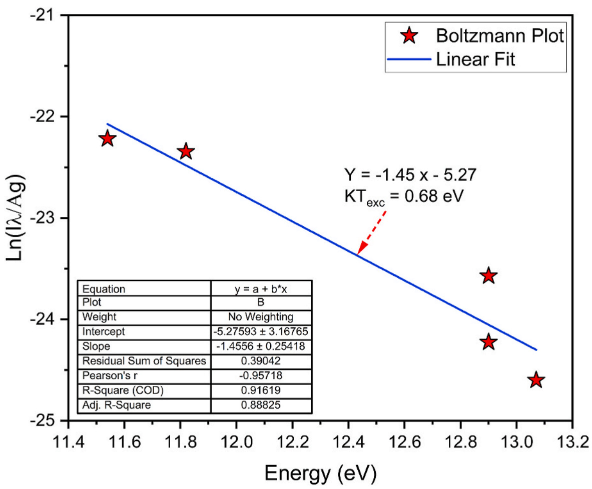

Fig. 4. Typical Boltzmann plot used for estimating excitation temperature of the Argon plasma.

enzymes [12,19,34]. However, prolonged exposure (420 s) led to a significant decline in germination percentage. This may be due to reasons such as DNA damage, oxidative stress, membrane damage, protein denaturation, nutrient depletion, and the induction of apoptosis-like processes [18].

Mean germination time (MGT) pertains to the mean duration required for a cluster of seeds to undergo germination under specific circumstances. This parameter is frequently employed in germination research to evaluate the general rate and effectiveness of seed germination. A reduced MGT signifies a quicker germination of seeds, whereas an extended MGT indicates a slower germination process [35]. Our results indicate that coriander seeds subjected to NTP for 180 s demonstrated a decrease in the MGT value by 1.32% compared to untreated seeds. During this short NTP exposure of 180 s, the treatment might trigger specific physiological responses that lead to the breakage of seed dormancy and an enhancement of germination processes. NTP generates various RONS, UV radiation, and electric fields, leading to the activation of enzymes and fostering diverse biochemical reactions within the seed [34]. As a result, the seeds might experience a positive stimulatory effect, resulting in a marginal reduction in the MGT when compared to the untreated seeds. In contrast, prolonged NTP exposure for 420 s led to adverse effects on the seeds [Table 1]. The continuous exposure to intense RONS, UV radiation, and electric fields can cause excessive stress and damage to the seeds. This damage may disrupt critical physiological processes involved in germination, such as hormone regulation, water uptake, and nutrient transportation [36]. The oxidative stress induced by prolonged NTP exposure could also have a negative impact on seed viability, reducing germination efficiency and leading to an elevated MGT compared to untreated seeds. Therefore, the observed variations in mean germination time (MGT) of coriander seeds subjected to NTP for different durations can be linked to the intricate and multifaceted effects of NTP on seed physiology and dormancy mechanisms.

The coefficient of variation of germination time (CV_t) serves as a valuable instrument in germination studies, providing valuable information into the dependability and uniformity of the germination process under particular experimental circumstances [27]. Coriander seeds exposed to NTP for 180 s exhibited a 11.6% reduction in CV_t compared to untreated seeds [Table 1]. A lower CV_t implies greater uniformity and consistency in germination times within the seed group [Table 2]. However, no significant differences in CV_t were observed between untreated seeds and those treated with NTP for 300 s and 420 s. Here, a higher CV_t signifies increased variability in germination times, indicating that the seeds exhibited a less uniform and more widely dispersed germination pattern.

The coefficient of velocity of germination (CVG) allows us to assess the efficiency and rapidity of germination within a given batch of seeds. A higher CVG value suggests that a greater proportion of seeds experienced swift germination, highlighting a more efficient and timely process. On the other hand, a lower CVG value indicates a slower germination rate and less efficiency [27]. Coriander seeds subjected to NTP for 180 s and 300 s demonstrated a rise in the CVG value by 1.3% in comparison to the untreated seeds. Conversely, seeds treated with NTP for 420 s showed a decrease in CVG by 4.9% compared to the untreated seeds [Table 1]. These results suggest that the duration of NTP exposure can influence the germination speed, with shorter exposure times potentially enhancing germination, while longer exposure times may have a negative impact on germination efficiency.

The Germination index (GI) emphasizes both the percentage of germination and the speed at which germination occurs by assigning higher weights to seeds germinated on the first day and progressively lower weights to seeds germinated on later days, with the lowest weight for seeds germinated on the last day. A higher GI value indicates a higher percentage and a higher rate of germination, while a lower value suggests a lower percentage and a slower germination process [37]. It was observed that NTP treatment affects seed germination index (GI) by stimulating beneficial changes in seed physiology and metabolic processes during shorter exposures (180 s and 300 s). Seeds treated with NTP for 180 s and 300 s demonstrated a rise in the germination index (GI) by 43.7% and 14.3%, respectively, in comparison to the control group [Table 1]. This leads to faster and synchronized germination with higher GI values. In contrast, seeds exposed to NTP for 420 s showed a decrease in GI by 27.8% compared to the control group. Prolonged NTP exposure (420 s) might induce excessive stress and damage cellular structures, resulting in reduced germination efficiency and lower GI values in comparison to the untreated one.

The uncertainty of the germination process (U) serves as a crucial metric to measure the diversity and uniformity of germination results. It provides significant understanding into the reliability and predictability of germination outcomes within a particular experimental condition. A lower uncertainty value signifies a more reliable and consistent germination process, enhancing the overall confidence in the experimental outcomes [27,38]. Coriander seeds exposed to NTP for 180 s exhibited a decrease in the U-value by 17.8% compared to the control group [Table 2]. However, no notable differences in the U-value were noticed between the control group and seeds treated with NTP for 300 s and 420 s. This suggests that a shorter NTP exposure (180 s) was more effective in positively influencing the germination process in coriander seeds than longer exposures.

Table 1
Comparative Analysis of Germination Parameters "Germination percentage (GP), Mean germination time (MGT), Coefficient of variation of germination time (CV_t), Coefficient of velocity of germination (CVG), and Germination index (GI)" among untreated and NTP exposed seeds.

Treatment Time	GP (%)	MGT (days)	CV_t (%)	CVG (%)	GI
Untreated	58.3 ± 1.52^{c}	9.82 ± 0.01^{b}	12.69 ± 0.26^{ab}	10.18 ± 0.01^{b}	15.06 ± 0.4^{c}
180 s	82.6 ± 1.15^{a}	9.69 ± 0.01^{c}	11.22 ± 0.26^{cd}	10.31 ± 0.01^{a}	21.65 ± 0.3^{a}
300 s	65.6 ± 1.52^{b}	9.71 ± 0.05^{bc}	12.17 ± 0.69^{bc}	10.29 ± 0.05^{a}	17.22 ± 0.4^{b}
420 s	44.0 ± 2.64^{d}	10.3 ± 0.06^{a}	13.90 ± 0.90^{a}	9.68 ± 0.06^{c}	10.8 ± 0.5^{d}

Distinct letters (a-d) within same column indicate a significant variation among the groups, as determined by one-way ANOVA and Tukey's multiple comparison test with a significance level of $p < 0.05$. Error bar represents standard deviation ($n = 3$).

Table 2
Comparative Analysis of Germination Parameters "Uncertainty of germination process (U), Synchronization Index (Z), Mean Daily Germination (MDG), Peak Value (PV), and Germination Value (GV)" among untreated and NTP exposed seeds.

Treatment Time	U (bit)	Z	MDG (%)	PV	GV
Untreated	2.19 ± 0.03^{a}	0.27 ± 0.01^{b}	2.15 ± 0.05^{c}	4.79 ± 0.10^{c}	10.33 ± 0.5^{c}
180 s	1.79 ± 0.03^{b}	0.36 ± 0.01^{a}	3.07 ± 0.04^{a}	7.45 ± 0.06^{a}	22.93 ± 0.5^{a}
300 s	2.17 ± 0.05^{a}	0.28 ± 0.05^{b}	2.44 ± 0.05^{b}	5.52 ± 0.10^{b}	13.51 ± 0.8^{b}
420 s	2.31 ± 0.08^{a}	0.26 ± 0.06^{b}	1.63 ± 0.08^{d}	3.39 ± 0.11^{d}	5.56 ± 0.48^{d}

Distinct letters (a-d) within the same column indicate a significant variation among the groups, as determined by one-way ANOVA and Tukey's multiple comparison test with a significance level of $p < 0.05$. Error bar represents standard deviation ($n = 3$).

The synchronization index (Z) quantifies the uniformity and consistency of seed germination within a group. A value of 1 means perfect synchronization, with all seeds germinating simultaneously. A value less than 1 indicates less synchronization, with seeds germinating at different times [27]. Seeds subjected to NTP for 180 s showed an increase in the synchronization index (Z) of 33.3% in comparison to the control group. A higher Z (180 s) suggests more consistent germination, aiding uniform crop growth. However, no notable differences in the synchronization index were seen among the control group and seeds treated with NTP for 300 s and 420 s [Table 2], indicating a lower Z (0, 300 s, and 420 s) may lead to uneven growth, requiring additional management efforts.

Mean daily germination (MDG) pertains to the average quantity of seeds that sprout within a defined timeframe on a daily basis. This measure offers valuable insights into the germination rate and assists researchers or cultivators in tracking and comprehending the day-to-day advancement of seed germination. NTP treatment affects MDG by influencing the physiological processes of coriander seeds. We noticed that seeds exposed to NTP for 180 s and 300 s demonstrated a rise in MDG by 42.8% and 13.5%, respectively, compared to the control group [Table 2]. However, seeds treated with NTP for 420 s showed a decrease in MDG by 24.18% compared to the untreated seeds. Short exposures (180 s and 300 s) might trigger beneficial responses, like enzyme activation and cell growth stimulation, leading to enhanced germination. Conversely, prolonged exposure (420 s) results in adverse effects due to oxidative stress and cellular damage, negatively impacting germination. The variation in MDG after NTP treatment can be attributed to the duration of exposure, with short durations being beneficial and longer durations potentially detrimental to germination.

Germination Value (GV) is an index that considers both the speed and completeness of seed germination, combining the proportion of successfully germinated seeds and the duration taken for germination [39]. The observed changes in GV after NTP treatment can be explained by the varying effects of the treatment on seed physiology. NTP exposure for 180 s and 300 s resulted in increased GV (121.8% and 30.8%, respectively, compared to the control group), indicating positive impacts on seed germination [Table 2]. These durations might stimulate beneficial physiological processes, such as enzyme activation, enhanced membrane permeability, and hormone production [13,19]. A higher GV values observed in our study indicate seeds have both high germination percentages and rapid germination rates. However, when seeds were treated with NTP for 420 s, GV decreased by 46.2%, compared to the untreated seeds, suggesting detrimental effects due to prolonged exposure. Prolonged NTP treatment may have induced oxidative stress, disrupted metabolic pathways, and caused physical damage to seed tissues, leading to inhibited germination [18]. Additional investigation is required to gain a comprehensive understanding of the mechanisms behind these responses.

3.3.1. Time for x% germination

T_{50} refers to the duration needed for 50% of the seeds in a specific population to undergo germination. A shorter T_{50} value typically indicates higher seed quality, faster germination rates, and the likelihood of producing healthy seedlings [40,41].

Our findings supported that seeds exposed to NTP for 180 s positively affect seed germination characteristics [Table 3]. A suitable dose of NTP treatment might improve seed germination characteristics by increasing permeability, activating enzymes, altering hormonal balance, eliminating pathogens, stimulating DNA and cell repair, and activating stress-response genes [13,34,42].

3.4. Water imbibition rate

For this investigation, coriander seeds were subjected to NTP treatment for varying durations of 0, 180 s, 300 s, and 420 s, respectively. Each experimental condition involved 50 seeds, and the experiment was conducted in triplicate for each seed variety.

Table 3
Time taken for a specific percentage of seeds to undergo germination.

Treatment Time	T_{10} (days)	T_{25} (days)	T_{50} (days)	T_{75} (days)	T_{90} (days)
Untreated	8.08 ± 0.01^{b}	8.51 ± 0.01^{b}	9.21 ± 0.00^{b}	9.87 ± 0.01^{b}	11.02 ± 0.14^{b}
180 s	8.11 ± 0.01^{b}	8.46 ± 0.00^{c}	9.04 ± 0.00^{d}	9.64 ± 0.01^{c}	10.13 ± 0.17^{c}
300 s	8.01 ± 0.02^{c}	8.42 ± 0.01^{d}	9.10 ± 0.02^{c}	9.79 ± 0.03^{b}	10.77 ± 0.12^{b}
420 s	8.28 ± 0.02^{a}	8.94 ± 0.01^{a}	9.55 ± 0.01^{a}	10.4 ± 0.09^{a}	11.75 ± 0.18^{a}

Distinct letters (a-d) within the same column indicate a significant variation among the groups, as determined by one-way ANOVA and Tukey's multiple comparison test with a significance level of $p < 0.05$. Error bar represents standard deviation ($n = 3$).

Post-treatment, the weight of the seeds was meticulously measured using an electronic balance (MG124Ai, Bel Instruments, Italy). These seeds (control and treated) were then placed in separate beakers, each filled with 100 mL of distilled water. Over a period of 10 h, the water absorption of the seeds was monitored at regular intervals of every 2 h using Equation (14) [43]. This enabled the assessment of the imbibition rate, providing insights into how quickly the seeds absorbed water during the soaking process.

$$\text{Water uptake } (\%) = \frac{\text{Final mass } (m_f) - \text{Initial mass } (m_i)}{\text{Initial mass } (m_i)} \times 100 \tag{14}$$

The water imbibition process is pivotal in disrupting the dormant stage of the embryo and has a significant impact on seed germination. Our findings revealed that seeds treated with NTP (180 s and 300 s) and soaked in water demonstrated increased water absorption compared to untreated seeds [Fig. 5]. In general, seeds exhibit hydrophobic properties. Exposure to NTP for a specific duration may involve RONS found in the discharge, potentially contributing to the surface etching or functionalization of the seed coat. This process has been observed to increase the roughness of the seeds, resulting in a more granular texture, as documented by various researchers using SEM images [44,45]. Various scholars have suggested a clear link between the water contact angle (WCA) and water absorption in seeds subjected to plasma [18,44]. Moreover, a recent investigation found that NTP treatment increased the hydrophilicity of the seed coat, enhancing water uptake into the seeds and overcoming obstacles to water penetration [46]. So in our study, the NTP treatment might likely improve the seeds' surface properties, making them more hydrophilic and facilitating water penetration as discussed by various researchers [44,47]. These modifications may have removed water-repellent compounds and activated germination processes, contributing to the observed effect. In contrast, compared to control and treated (300 s and 400 s), prolonged NTP treatment (420 s) resulted in a decline in the water imbibition rate of the seeds. This could be attributed to various factors, including excessive surface modification, damage to seed tissues, the formation of inhibitory compounds, depletion of essential nutrients, and the activation of stress responses. This increased water absorption rate (180 s and 300 s) may be linked to their higher GP, lower MGT, higher GI and improved vigor as obtained in our study. The NTP treatment likely improved the seeds' water uptake capacity, positively influencing their ability to germinate and initiate growth.

3.5. Water contact angle measurements

Assessing the wettability and permeability of seed surfaces entailed measuring the water contact angle (WCA) to gauge the level of hydrophilicity. The germination potential of a seed relies on its capacity to absorb water, with surfaces that are hydrophilic promoting germination more effectively than hydrophobic ones. Therefore, promoting seed germination necessitates enhancing hydrophilicity, as evidenced by a reduction in WCA on the seed surface. The static WCA was measured using a goniometer, (manufactured by Ramé-Hart Instrument Co., USA), and the assessment was facilitated through the employment of Drop Image software. A droplet of approximately 2 μL of distilled water was carefully placed on the surface of coriander seeds to ascertain the contact angle. These measurements were carried out in ambient conditions promptly following the NTP treatment using Equation (15) [43]. To ensure accuracy in the measurement of water contact angle, the investigation utilized 10 seed samples for each group to calculate the average WCA value.

$$\cos\theta = \frac{\gamma_{vs} - \gamma_{ls}}{\gamma_{vl}} \tag{15}$$

where, γ_{vs}, γ_{ls}, and γ_{vl} are the interfacial tension between the solid and vapor, solid and liquid, and liquid and vapor respectively.

The untreated seeds displayed initial water contact angle (WCA) and surface free energy (SFE) measurements of 106.53° ± 5.13°

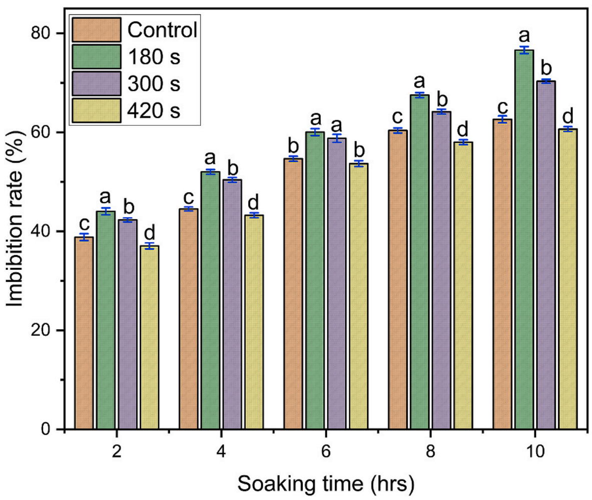

Fig. 5. Variation in imbibition rate due to plasma exposure. Distinct letters (a–d) represent a significant variation among the group as determined by one-way ANOVA and Tukey's multiple comparison test with a significance level of $p < 0.05$. Error bar represents standard deviation (n = 3).

and 19.12 ± 2.98 mJ/m^2, respectively. Following 180 s, 300 s and 420 s treatment with NTP, the WCA and SFE gradually decreased to (66.21° ± 1.83°, 59.45° ± 2.49°, and 58.21° ± 4.31°) and (44.05 ± 1.13 mJ/m^2, 48.17 ± 1.51 mJ/m^2, and 48.97 ± 2.60 mJ/m^2), respectively demonstrating the substantial impact of the NTP treatment on the surface properties of the seeds [Fig. 6].

The observed alterations can be ascribed to the chemical processes involved in modifying the surface of the seed, leading to enhanced hydrophilicity. NTP treatment introduces various reactive species like hydroxyl (OH) radical, ionized N_2 molecules, ozone (O_3), electrons, and ultraviolet radiation from the discharge (Fig. 3 illustrates this process). The interaction between these species and the organic surfaces of the seeds could potentially result in the partial breakdown of surface polymeric chains, leading to the creation of functional groups containing oxygen and nitrogen [44,47–50]. This introduction of new hydrophilic functional groups or the enhancement of surface porosity could modify the seed surface, encouraging the development of pores or cavities in the seed integument, thus enhancing water penetration. As a result, treating the seeds with NTP improves the interaction between their surfaces and water, leading to improved wettability. Additionally, NTP treatment might also induce oxidation of surface fibers and establish covalent cross-links between them, consequently diminishing the seeds' hydrophobic nature and augmenting their overall wettability, as observed in our study.

3.6. Mass loss

Three replicates of 50 coriander seeds for each group (control and treated) were weighed using an electronic weighing machine (MG124Ai, Bel Instruments, Italy). Each set of seeds was treated individually for a specific duration (180, 300, and 420 s). Immediately after undergoing NTP treatment, the seeds' masses were measured to assess the extent of mass loss using Equation (16) [43].

$$\text{Mass loss }(\%) = \frac{\text{Initial mass }(m_i) - \text{Final mass }(m_f)}{\text{Initial mass }(m_i)} \times 100 \tag{16}$$

The increase in mass loss with prolonged treatment duration (180 s, 300 s, and 420 s) suggests that the effects of NTP become more pronounced with longer exposure times. It was noted that seeds exposed to NTP for 180 s, 300 s, and 420 s exhibited an increase in mass loss by 15.8%, 17.9%, and 22.2%, respectively, in comparison to the control group [Fig. 7]. The observed increase in mass loss in coriander seeds undergoing NTP treatment for different durations can be attributed to the impacts of NTP on the physical and chemical properties of the seeds. NTP, being a partially ionized gas with reactive species, can interact with the surface of the seeds, leading to the breakdown of organic compounds and the decomposition of complex molecules into simpler ones, resulting in mass loss. Additionally, NTP treatment may cause surface modifications, increasing surface roughness or porosity, and promoting chemical reactions that release volatile compounds and gases, further contributing to mass loss [18,51,52]. Structural changes induced by prolonged NTP treatment may also weaken the integrity of the seeds' tissues, leading to physical degradation and subsequent mass loss [53]. The combination of these processes under NTP treatment can explain the observed increase in mass loss in coriander seeds in our case.

3.7. Estimation of seedling length and vigor index

Coriander seeds were subjected to plasma treatment prior to sowing, aiming to assess the subsequent seedling length. After a period of 25 days from sowing, a careful extraction of several seedlings from the germination tray was performed, ensuring minimal disturbance to their root systems, to facilitate the measurement of their lengths. The lengths of the seedlings from both the control group and the NTP-treated group were measured using a ruler. Furthermore, the measurements of the seedling lengths from both the control group and the NTP-treated group revealed no significant variation, indicating that the NTP treatment had no noticeable effect on the initial growth of the coriander seedlings [Fig. 8 (a)].

The vigor index effectively captures the combined impact of seed germination percentage and seedling growth, providing valuable

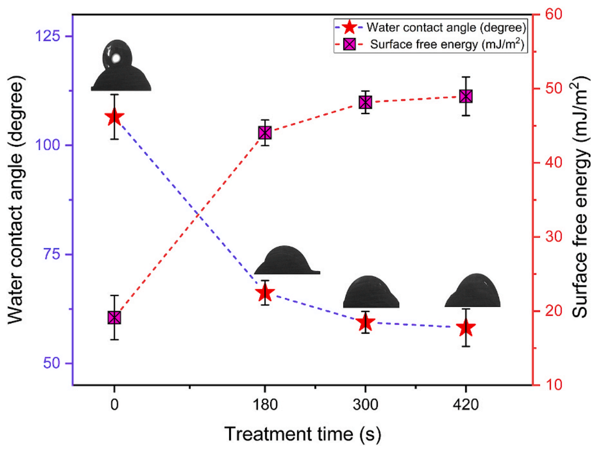

Fig. 6. Variation of water contact angle (WCA) and surface free energy (SFE) on seed surface as a function of plasma exposure time.

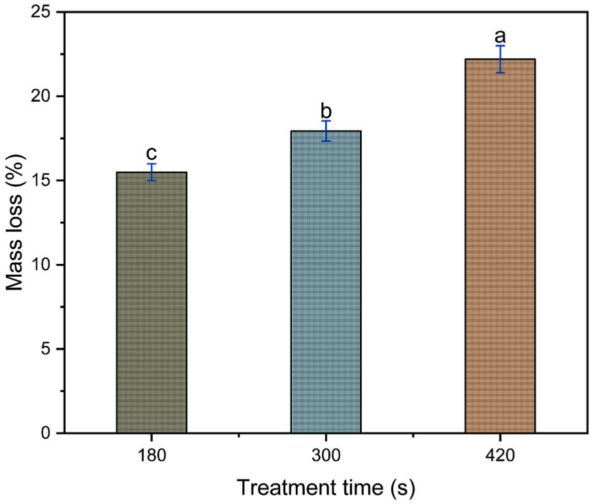

Fig. 7. Variation in mass loss due to plasma exposure. Distinct letters (a–c) indicate a significant variation among the group as determined by one-way ANOVA and Tukey's multiple comparison test with a significance level of $p < 0.05$. Error bar represents standard deviation ($n = 3$).

insights into seed quality and vitality [Equation (17)] [29].

$$\text{Vigor index (I)} = \text{Seedling length (SL)} \times \text{germination percentage (GP)} \quad (17)$$

The results of the NTP treatment on coriander seeds demonstrate that an optimal exposure duration (180 s) can lead to significant improvements in vigor, while prolonged treatment (420 s) may have adverse effects, underscoring the importance of carefully optimizing the treatment conditions for different seed types to achieve the desired outcomes [Fig. 8 (b)]. The notable increase in vigor index after 180 s of NTP treatment can be attributed to the combined effects of improved germination percentage and favorable seedling growth. The treatment might activate beneficial stress responses, enzymes, and hormonal regulation, promoting efficient metabolic processes and enhanced cell membrane permeability [45,54–56]. These factors collectively contributed to the observed boost in both germination percentage and seedling length, resulting in a substantial increase in the overall vigor index as observed in our study. In contrast, the decrease in vigor index observed after prolonged (420 s) treatment can be attributed to the adverse effects of excessive stress and oxidative damage on the seeds. Prolonged exposure to NTP might have overwhelmed the seeds' capacity to cope with the reactive species generated during the treatment [Fig. 3], leading to detrimental effects on both the percentage of germination and the growth of seedlings. The extended exposure might disrupt cellular processes, negatively impacting the metabolic activities, hormonal regulation, and cell membrane integrity. As a result, both germination percentage and seedling growth were compromised, leading to the observed decrease in the overall vigor index.

4. Conclusions

This study reveals the impact of non-thermal plasma treatment on the germination characteristics of coriander seeds. Short-duration treatments of 180 s and 300 s significantly improve germination percentage, germination index, coefficient of velocity of germination, mean daily germination, and vigor index. These beneficial effects might be attributed to the activation of enzymes, enhanced membrane permeability, dormancy breakage, and favorable hormonal regulation induced by NTP-generated reactive oxygen and nitrogen species. However, prolonged NTP exposure for 420 s leads to adverse effects, resulting in reduced germination percentage, germination index, and vigor index. The detrimental outcomes might be associated with oxidative stress, cellular damage, and disruptions in metabolic processes caused by prolonged exposure to intense NTP-generated reactive species. The results emphasize the importance of optimizing NTP treatment durations for specific seed types to achieve desired improvements in germination characteristics. Overall, this investigation provides valuable understanding regarding the potential applications of NTP in enhancing seed germination and highlights the need for further research to fully comprehend the underlying mechanisms governing the responses of seeds to NTP treatment.

5. Limitation of the study

The limitations of the study include a restricted sample size, the use of a custom-designed 11 kV rms, 50 Hz power supply for discharge generation, and the inability to conduct comprehensive analyses of various germination aspects, as well as a detailed assessment of biochemical and molecular factors influencing seed germination and growth.

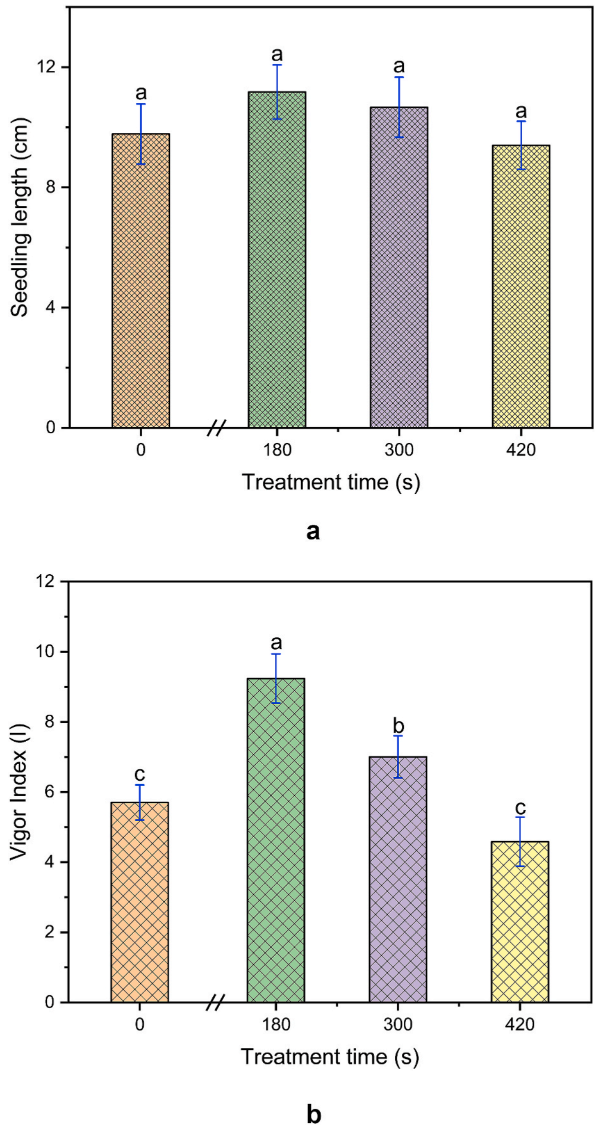

Fig. 8. (a) Variation in seedling length due to plasma exposure (b) Variation in vigor index due to plasma exposure. Distinct letters (a–c) represent a significant variation among the group as determined by one-way ANOVA and Tukey's multiple comparison test with a significance level of $p < 0.05$. Error bar represents standard deviation ($n = 3$).

Data availability

The data that supports the findings of the study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Rajesh Prakash Guragain: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hom Bahadur Baniya:** Visualization, Data curation. **Deepesh Prakash Guragain:** Writing – review & editing, Validation, Software, Formal analysis. **Deepak Prasad Subedi:** Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: RAJESH PRAKASH GURAGAIN reports financial support and equipment, drugs, or supplies were provided by the Kathmandu

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