

Non-Thermal Atmospheric Pressure Plasma Treatment to Improve Seed Germination and Seedling Growth of Two Okra (*Abelmoschus esculentus* (L.) Moench) Varieties

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This study explores the application of non-thermal atmospheric plasma treatment to improve seed germination and seedling characteristics of two varieties of Okra (*Abelmoschus esculentus* var. 'Smooth Green' and 'Red Ruby') seeds. Two variants of Okra were obtained, with 660 seeds each. Seeds were directly treated with atmospheric pressure plasma (APP) and subjected to germination testing and seedling characterization and compared with untreated seeds. Both germination testing and seedling characterization were done in split-plot design in Completely Randomized Design (CRD) with APP treatment as the main factor and the variety as the subplot with 3 replicates per treatment and 2 subsample of 30 seeds each. Germination was observed daily for 14 days, and sowing commence thereafter for 2 wks. Characteristics such as germination index, germination percentage, time spread of germination, mean germination time, were determined. Further, seedling shoot and root length and total plant length and vigor index II were also determined after sowing the seedlings in pots with moist coir dust. Data was analyzed using two-way Analysis of variance. In all parameters observed, significant differences were observed for both germination and seedling characteristics. Higher germination percentage, more uniform and earlier germination with shorter germination time were observed on APP treated seeds. Generally, longer plants as indicated by longer shoot and root lengths were observed on APP treated seeds across varieties. In terms of germination index, APP treated seeds also had higher germination and more vigorous seedlings compared to untreated seeds across varieties. These findings suggest that direct non-thermal atmospheric plasma exposure may be effective at stimulating rapid germination and seedling growth for both 'Red Ruby' and 'Green Smooth' varieties.

Keywords: *Abelmoschus esculentus*, Atmospheric pressure plasma, plasma agriculture, seedling growth, seeds

INTRODUCTION

Okra (*Abelmoschus esculentus* L.), or lady's finger, is a fast-growing, tropical vegetable crop under the Malvaceae family. Botanically, the plant has an upright growth habit, lobed leaves, and produce mucilaginous green pods. These green pods were harvested before maturity and consumed as a vegetable in the Philippines and other parts of the world. Okra pods are rich sources of fiber, vitamin A, C, folate, and antioxidants (Baskin et al. 2001). Okra thrives well in tropical and subtropical climates making it very well suited to the agro-climatic conditions of the country. The seeds of Okra are round, hard-coated, and exhibit physiological dormancy, often resulting in low viability and poor germination rates under suboptimal storage or planting conditions (Musara et al. 2015). Further, hard seedness is another problem in Okra resulting in erratic and low viability of seeds (Mohammadi et al. 2012). Low and erratic germination are critical challenges that affect successful crop establishment therefore early germination and field establishment is important to promote timely harvesting and marketing of vegetables like Okra (Denton et al. 2013).

To address germination challenges, researchers have explored emerging technologies such as Cold or Non-thermal Plasma Treatment in improving germination of crops. Plasma can be any gas (air, oxygen, argon, nitrogen, etc.) that is being ionized using an electric field. This ionization, done even under low atmospheric pressure, may form electrons, ions, UV, thermal radiation, and reactive species, such as reactive oxygen species (ROS). Waskow and Furno (2021) further discussed that to produce plasma, a plasma jet was used where a dielectric barrier discharge (DBD) is the plasma source. The DBD produces plasma by "alternating high voltage (kV) between two electrodes, where a volume of gas flows between the electrodes or on the surface of the DBD. The different reactive species that may be produced through this include superoxide ($O_2^{\cdot-}$), hydrogen peroxide (H_2O_2), and hydroxyl radical ($OH\cdot$), and reactive nitrogen species (RNS) such as nitric oxide ($NO\cdot$), peroxyxynitrite ($ONOO\cdot$) and nitrogen dioxide radical ($NO_2\cdot$) (Waskow and Furno 2021).

These reactive species, which can be produced using atmospheric pressure plasma treatment, were documented to be key regulatory players for germination and other plant developmental phases. ROS were observed to stimulate Gibberellic acid biosynthesis (Huang et al. 2019) and were found to be associated with ABA degradation (Ishibashi et al. 2017).

Plasma treatment may be conducted using different type of air (Oxygen, Argon, Normal Air) and in different conditions (vacuum or non-vacuum) and using different mechanism jets (Dielectric Barrier discharge or Glow discharge). In this study, non-thermal atmospheric pressure plasma priming is a seed priming technique that utilizes direct exposure of seeds to Atmospheric Pressure Plasma using an atmospheric pressure plasma jet (APPJ). Through APPJ, the atmospheric pressure air is ionized enhancing the air with reactive oxygen and nitrogen species (ROS and RNS). These ROS and RNS have different effects on plants. Direct non-thermal plasma treatment may be a possible solution and novel technique to improve and hasten germination of seeds, most especially the uneven and low germination of Okra seeds. Various crops, such as wheat, have been exposed to non-thermal plasma with significant positive effects on germination and early growth observed (Sera et al. 2010). Due to the difficulties associated with seeds of Okra, these seeds are a prime candidate for the application of cold plasma treatments.

In Okra, Sehrawat et al. (2017) and Kumar et al. (2018) explored the use of glow discharge plasma of Oxygen gas while Shah et al. (2023) utilized the use of DBD (Shah et al. 2023). In Okra, the effect of direct plasma treatment using atmospheric pressure plasma jet remain underexplored most especially using different varieties (Wong et al. 2023; Ismaniza et al. 2024). However, as of this writing, no studies on the use of non-thermal plasma were reported involving two varieties of Okra in the Philippines. Further, documentation of germination response were not well documented in these studies.

The objective of the study is to analyze the effect of direct non-thermal plasma treatment on germination and initial growth of seeds of two varieties of Okra namely 'Red Ruby' and 'Green Smooth'. Specifically, this was done by assessing the significant effects of APP exposure on germination response and seedling characteristics of Okra seeds.

METHODOLOGY

Research Design

The experiments were laid out in a Split-plot completely randomized design (CRD) with three replicates and two subsamples each for the germination test. The main factor was the type of Treatment (App-treated and untreated (control)) and the subplot is cultivar/ variety (Red Ruby and Green Smooth).

Preparation of seeds

Seeds of Okra (*Abelmoschus esculentus*) were used in the study. Two cultivated varieties were tested for the study, namely 'Red Ruby' (RR) and 'Green Smooth' (GS). The cv. 'Red Ruby' (RR) is a Red colored Okra variety while the cv. 'Green Smooth' is a green Okra variety. The seeds were sourced from a private seed corporation bought using an online shopping platform. Seeds were preselected and only seeds free from physical damage were used in the study. In the experiment, a total of 600 seeds per variety were used for a total of 1200 seeds.

Preparation of seed treatments

The experiments were laid out with three replicates and two subsamples each for the germination test. Two sets of 50 seeds were used as subsamples for a total of 600 seeds per variety of Okra. In the study, 300 seeds per variety or a total of 600 were either treated or exposed to atmospheric pressure plasma jet for 3 sec on both sides for a total of 6 sec of exposure. The remaining seeds were not exposed to atmospheric pressure plasma to serve as a control. The APPJ (Park et al. 2013 and Malapit and Baculi 2021) used in this study was set up in the Research Laboratory of the Philippine Science High School Main campus. The power source used is a 10 kV Neon sign transformer, air was pumped by a 55 L min⁻¹ air compressor, two 1.6 mm diameter Tungsten rods were used as the electrodes, and a glass enclosure with a small hole was made to contain the plasma and form the jet. The distance between the tip of the APPJ and the seeds was maintained at 1 cm. (Dela Cruz et al. 2024)

For the seedling characterization, 10 seedlings per replicate for a total of 120 seeds were used. Seedlings were planted in pots filled with the seeds were sown in a sterile potting medium composed of commercial garden soil, compost, and pumice. The moist coco coir medium was placed in well-drained ceramic pots resting on benches and were provided with sufficient sunlight and water to support growth. Seedlings were grown for 15 days before the measurements of different plant parameters.

Germination test

Treated and untreated seeds were subjected to a germination test using the top-of-paper method. A day after sowing, manual counting of germinated seeds was done. A germinated seed is characterized by having its radicle protrude from the seed. Daily observation was done until the 14th day of germination. Seeds were equidistantly laid in Petri plates lined with moist tissue paper and placed on a well-ventilated bench at the Research laboratory in the Philippine Science High School Main Campus. The set-up was sprayed with enough distilled water during the testing period of 14 days to maintain the set-up moist. Each Petri plate, as a subsample, has 50 seeds equidistantly placed. Average final germination percentage (GP%), average seed vigor index (SVI), and average germination time (AGT) were computed. Further, average first and last days of germination were determined and used to compute the average time spread of germination for each subsample.

Table 1. Summary of the formulae used in the study

Parameter	Formula
Germination Percentage (%)	$((\text{Total no. of seedlings}) / (\text{No. of seeds sown})) \times 100$
Seed vigor Index	$n/1+\dots+n/7$; n = no. of seedlings
Mean Germination Time (days)	$\sum (\text{Daily no. of germinated seeds} \times \text{no. days from beginning of test}) / (\text{Total germinated seed at final count})$
Time spread of germination (days)	Last Day of germination (LDG) – First day of germination (FDG)
Vigor Index I	Standard germination (%) $\times$ Average seedling length (cm)
Vigor Index II	Germination Percentage (%) $\times$ Mean Seedling Dry Weight (mg or g)

Average Percent germination (%) (GP). Germinated seeds were counted daily at 5:00 PM. GP was calculated using the formula shown in Table 1. Higher germination percentage means higher seed viability.

Average Seed Vigor Index (SVI). Daily counting of germinated seeds was done for 14 days. SVI was then computed (Table 1). A high SVI indicates high seed vigor, which reflects both a high germination rate and uniformity.

Average Germination Time (MGT). This is a measure of time that takes for seeds to germinate. It focuses on the day where most of the seeds have germinated. A lower AGT indicates a shorter time for seeds to germinate (Al-Mudaris, 1998).

Time Spread of germination (TSG). This is the time in days between the first and last day of germination events in the seed lot. Higher TSG indicates greater difference on the germination between the fast and slow germination seeds of the lot/ seed batch (Al-Mudaris, 1998).

After germination and seedling growth, morphological seedling parameters were also measured. Morphological seedling parameters include root, shoot, total plant biomass, and plant height. Further, other vigor indices were calculated.

Root, Shoot and Total Plant Biomass. The seedling growth was measured by selecting 10 seedlings per subsample. Root and shoot weights (in g) were also measured using an analytical balance to obtain fresh weight. Both root and shoot were oven dried at 70°C for 72 hr and their weights were determined using an analytical balance.

Vigor Index I (VI). This is used to assess the seedling vigor and overall health and growth potential of a batch of seed. This indicates that more seeds that germinate produce longer and healthier seedlings. Higher vigor Index I indicates strong seed vigor and likely better field performance.

Vigor Index II (VII). This was calculated by determining the sum of root and shoot dry weight and multiplied by the germination percentage. Higher seed vigor index means that the seed lot has high overall vigor and good health of seedlings from the

seed lot. Higher vigor index II means higher seedling quality and computed using the formula on Table 1.

Scanning Electron microscopy

Representative samples of APP treated and untreated Okra seeds of both Red Ruby and Green Smooth cultivars were sent to the Research Laboratory of the Philippine Science High School-Ilocos Region Campus for Scanning Electron Microscopy. The surface of seed coats was examined, and a qualitative comparison was done to determine changes across treatments.

Statistical Analysis

Seed germination and seedling data were analyzed using an independent Student's t-test for comparing treated and untreated for both varieties after meeting assumptions of normality and homoscedasticity at a 5% level of significance. Analysis was done using Statistical Tool for Agricultural Research (STAR) software (IRRI 2014).

RESULTS AND DISCUSSION

Effect of APP Treatment on Seed germination characteristics of two *A. esculentus* varieties

The effect of direct atmospheric pressure plasma treatment on germination characteristics of Okra were determined. Final germination percentage (%GP), seed vigor index, germination time and time spread of germination of Okra seeds treated by direct APP compared with untreated seeds for two varieties were shown (Table 2).

Significant differences were observed in the germination percentage of untreated and APP treated seeds for both varieties ($p=0.002$) where APP treated seeds had significantly higher germination percentages compared to untreated seeds ($p=0.001$). Further, interaction effects were not observed ($p=0.299$) hence showing that in terms of germination percentages, APP treated seeds had higher germination percentage for both varieties consistently.

In terms of SVI, interaction effects show that SVI is affected by both treatment ($p=0.001$) and variety ($p=0.002$). Moreover, significant differences were observed for untreated and treated seeds ($p=0.001$) and across varieties ($p=0.001$). This shows that for APP treated seeds germinate faster and more uniform compared to untreated seeds for both cultivars but show varied response in terms of its magnitude. Significant interaction between seed treatment (APP) and cultivar on germination time ($p=0.001$) were observed. The effect of APP treatment was significant ($p=0.001$) which shows that APP treated seeds generally germinate faster than untreated ones. However, the effect of variety was not significant ($p=0.76$). These results indicate the effectiveness of APP treatment in shortening germination time but not equal in magnitude across varieties. Table 1 shows that in 'Red Ruby', there is faster germination than in 'Green smooth'. Furthermore, in terms of time spread of germination, significant interaction ($p=0.001$) effects show that TSG is affected by both treatment ($p=0.001$) and variety ($p=0.001$). This result indicate

Table 2. Average Final Germination Percentage (GP, %), Seed vigor Index (SVI), and germination time (GT), and Time Spread of Germination of APP treated and Untreated seeds of two varieties of *A. esculentus*

Variety	Treatment	Germination Percentage (%)	Seed Vigor Index (SVI)	Germination Time	Time Spread of Germination
Green Smooth	APP Trt	94.44 ± 1.73 ^a	12.85 ± 0.49 ^a	2.38 ± 0.17 ^a	1.83 ± 0.41 ^b
	Untreated	83.89 ± 6.47 ^b	9.84 ± 1.10 ^b	2.86 ± 0.15 ^a	4.50 ± 0.55 ^a
Red Ruby	APP Trt	86.11 ± 4.91 ^a	12.55 ± 0.64 ^a	1.91 ± 0.12 ^b	2.00 ± 0.89 ^a
	Untreated	79.44 ± 3.28 ^b	7.43 ± 0.42 ^b	3.37 ± 0.18 ^a	2.33 ± 0.52 ^a
Cultivar (C)		*	*	ns	*
Treatment (T)		*	*	*	*
C x T		ns	*	*	*

Mean values _ SD are shown. Values with the same letter in the same column for one cultivar are not significantly different at $p < 0.05$. For ANOVA results, *, $p < 0.05$; ns, not significant.

Table 3. Average shoot, root and plant dry biomass and Vigor Index II of two varieties of *A. esculentus*.

Variety	Treatment	Shoot dry biomass (mg)	Root dry biomass (mg)	Total dry biomass (mg)	Vigor Index II
Green Smooth	APP Trt	21.17 ± 6.77 ^a	13.17 ± 6.43 ^a	34.33 ± 5.99 ^a	2735.53 ± 522.40 ^a
	Untreated	17.67 ± 4.08 ^a	10.17 ± 1.47 ^a	27.83 ± 3.76 ^b	2341.09 ± 393.03 ^a
Red Ruby	APP Trt	27.17 ± 2.56 ^a	10.83 ± 5.56 ^a	39.67 ± 6.44 ^a	3179.33 ± 797.12 ^a
	Untreated	23.67 ± 4.08 ^a	9.33 ± 3.27 ^a	33.00 ± 5.83 ^b	3118.86 ± 571.31 ^a
Cultivar (C)		*	ns	ns	*
Treatment (T)		ns	ns	*	ns
C x T		ns	ns	ns	ns

Mean values _ SD are shown. Values with the same letter in the same column for one cultivar are not significantly different at $p < 0.05$. For ANOVA results, *, $p < 0.05$; ns, not significant.

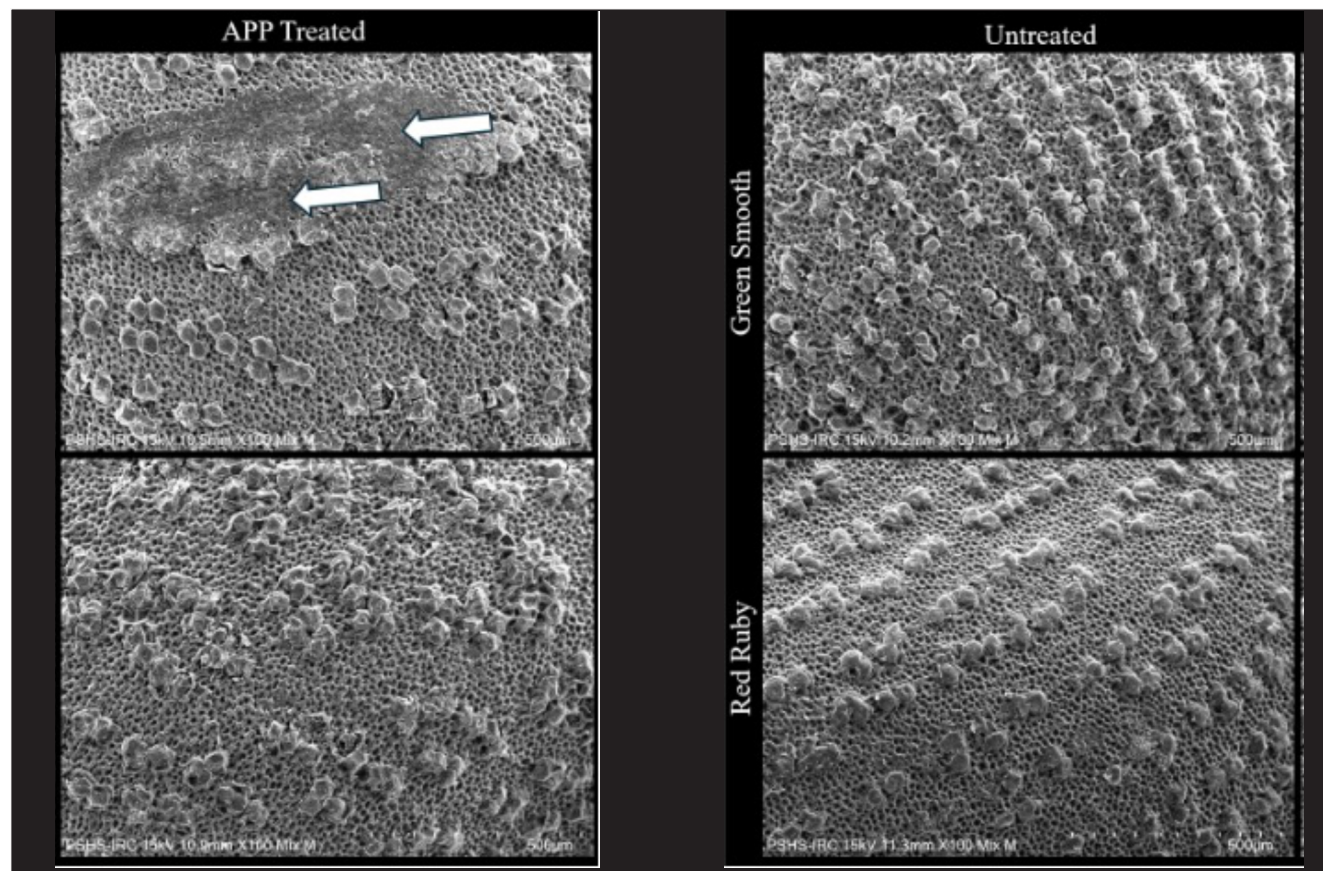


Figure 1. The SE micrographs of APP treated and untreated seeds of *A. esculentus* cv. 'Green smooth' and cv. 'Red Ruby' at 500× magnification. White arrows point to seed coat.

that APP treated seeds have shorter time spread to germinate and compared to untreated seeds for both cultivars but with varied magnitude.

The results of the present study corroborate with numerous researches in several crops like cotton (de Groot et al. 2018), maize (Gutierrez-Leon et al. 2025),

Table 4. Average shoot, root length, seedling height, and Vigor Index II of two varieties of *A. esculentus*.

Variety	Treatment	Root length (cm)	Shoot length (cm)	Seedling length (cm)	Vigor Index I
Green Smooth	APP Trt	7.40 ± 1.95 ^a	10.64 ± 1.62 ^a	18.04 ± 3.19 ^a	1705.39 ± 313.57 ^a
	Untreated	6.49 ± 2.21 ^b	9.77 ± 2.16 ^b	16.26 ± 4.19 ^b	1329.11 ± 311.89 ^b
Red Ruby	APP Trt	11.82 ± 1.76 ^a	14.31 ± 2.03 ^a	26.13 ± 3.38 ^a	2260.16 ± 354.19 ^a
	Untreated	9.61 ± 2.85 ^b	12.67 ± 1.46 ^b	22.28 ± 3.93 ^b	1771.97 ± 352.97 ^b
Cultivar (C)		*	*	*	*
Treatment (T)		*	*	*	*
C × T		ns	ns	ns	ns

Mean values ± SD are shown. Values with the same letter in the same column for one cultivar are not significantly different at $p < 0.05$. For ANOVA results, *, $p < 0.05$; ns, not significant.

soybean (Durcanyova et al. 2023), and barley (Benabderrahim et al. 2024) where they observed positive effects on germination characteristics of seeds exposed or treated with direct non-thermal plasma. In the study of Mohajer et al. (2024), cotton seeds were treated by exposing the seeds to dielectric barrier discharge plasma for 1 and 3 minutes. They observed that the highest germination percentage was observed on cotton seeds exposed to DBD plasma for 1 minute compared to control. In barley, direct treatment of seeds also increased germination and vigor of seeds (Benabderrahim et al. 2024). In soybean, Durcanyova et al. (2023) observed that plasma treatment stimulates germination which are caused by induction of biochemical processes and phytohormonal changes in the seed itself. Both studies in barley and in soybean concluded that plasma treatment of seeds before sowing improves germination and growth parameters. Moreover, Waskow et al. (2021) discussed that non-thermal plasma affects seeds through seed coat erosion, which cases increased wettability and increased water uptake. Additionally, Priatama et al. (2022) reported that plasma treatment of seeds increased the seed's pore sizes that allowed increased water imbibition, leading to increased and faster germination.

Since the primary initiator of germination is water being absorbed by seeds to hydrolyze starch, faster wettability may also increase or hasten germination. Further, surface mechanical modifications such as the removal of cutin or wax may happen when seeds are exposed to plasma. Figure 1 shows both SEM micrographs of APP treated and untreated seeds of *A. esculentus* cv. 'Green Smooth' and cv. 'Red Ruby' at 500× magnification.

In cv. 'Green Smooth', it can be observed that the APP treated seeds had eroded seed coats. Untreated seed coat of both 'Green Smooth' and 'Red Ruby' varieties has well-defined and tightly packed epidermal structures. This also shows that the seed coat appears intact and compact with relatively uniform arrangement when compared to untreated seeds. Further, the disorderly or looser structures may increase the surface's roughness. This may also promote increased porosity. The intact epidermal structures of the seed coat may limit both water and oxygen diffusion which may cause slower germination on untreated seeds. While untreated seeds have compact appearance, the surface of the seed coats of

treated seeds have visible abrasions caused by treatment. This can be considered as seed coat erosion. Plasma treatment altered the outer layer of the seed thus degrading its surface integrity that resulted in improved permeability and faster water absorption, causing faster germination. Further, Billah et al. (2020) indicated that exothermic reactions caused by heat of treatment may also melt the wax in the outer layer of the seed that also promoted water permeability resulting in faster germination.

Additionally, disorganized and disrupted epidermal structures were observed on both varieties but seed coat erosion was more evident on the seed coat of cv. 'Green Smooth' than on the seed coat of cv. 'Red Ruby' where only disruption and disorganization of epidermal structures were seen. This may be due to varietal differences in certain characteristics such as seed coat thickness, seed coat roughness, and composition (Mohajer et al. 2024). This differential response on APP treatment was also observed on two wheat varieties ('Apache' and 'Bezostaya 1') in a study by Staric et al. (2021) which indicated that cv. 'Apache' seeds respond and adapt better to cold plasma treatment compared to 'Bezostaya 1'. In this study, varietal difference in terms of response on germination and based on visual investigation of seed coats indicate that plasma treatment is cultivar dependent where they both respond positively to APP treatment, their magnitudes differ.

Overall, this present study showed that seed exposure to Atmospheric pressure plasma through the plasma jet have increased seed germination percentage, seed vigor, and shorten germination time and duration. Positive effects of plasma treatment on seeds were also observed by Wang et al. (2017) who investigated the effects of plasma treatment on cotton seeds. They stated that after using nitrogen plasma in open air, nitrogen oxides can be detected after treatment. These nitrogen oxides, according to them, promote germination signaling and inhibit dormancy. Increased seed vigor indicates that APP treated seeds germinate earlier and more uniformly. Further, seeds treated with APP had shorter germination time and had more rapid germination compared to their untreated counterparts. This is indicated by a low germination time and a higher coefficient of velocity of germination of treated seeds. Therefore, APP treatment not only improves the germinability of the Okra seeds but also increases the seed's speed of

germination, synchrony, and uniformity of germination of the seed lot.

Generally, APP treatment altered the seed coat morphology of both Okra varieties by increase roughness and creation of micro-etches that improved the seeds' ability to imbibe water that in turn activate enzymes in the seed which are important for faster germination. Moreover, the effect on the seedling of direct APP treatment for the 2 Okra varieties were also determined.

Effect of APP Treatment on seedling characteristics of two *A. esculentus* varieties.

The effect of direct atmospheric pressure plasma treatment on seedling characteristics of APP treated and untreated Okra seeds were determined. After growing the seedlings for 15 days in moist coco coir dust, average dry root, shoot, and total plant biomass were determined and vigor index 2 was calculated per treatment and analyzed (Table 3).

Table 3 shows no significant interaction of cultivar/variety and treatment was observed in shoot, root and total dry biomass and vigor index II. However, significant difference on total dry biomass was observed where APP treated seeds produced seedlings with higher total dry biomass than seedlings from untreated seeds for both 'Green Smooth' variety (34.33 ± 5.99 mg), and 'Red Ruby' variety (39.67 ± 6.44 mg). This shows that APP treatment improved the overall biomass accumulation across variety in Okra. Further, significant effects on variety were observed on shoot dry biomass and vigor index II where 'Red Ruby' had higher shoot dry biomass and vigor Index II values. More than the parameters measured above, root, and shoot length, plant height were determined 15 days after growth and the vigor Index I was calculated. The data were shown below (Table 4).

No significant interaction between treatment and variety on average shoot ($p=0.558$) and root lengths ($p=0.410$), total plant height ($p=0.637$) and vigor index I ($p=0.637$) were observed. This indicates that the effect of plasma treatment was consistent across the two Okra varieties. Moreover, significant differences were observed on treatment and variety on average shoot and root lengths, total plant height and vigor index I were determined.

Seedlings from Plasma treated seeds have significantly longer average shoots and roots and total plant height when compared to untreated seeds. Further, in terms of variety, 'Red Ruby' was observed to have longer roots and shoots and generally, plant height. Further, in terms of vigor index, higher vigor index I values were observed on APP treated seeds compared to untreated seeds and in terms of variety, 'Red Ruby' was shown to have higher vigor index I average values.

The consistent response to APP seed treatment as seen on the seedling characteristics suggest the positive and beneficial effect of direct APP treatment. Further, the consistent response in terms of longer root and shoot and taller plants of 'Red Ruby' in

comparison to the 'Green Smooth' may indicate varietal and genetic differences. Generally, the response observed on the seedling characteristics from APP treated seeds show consistent and positive effect of APP treatment regardless of variety.

The positive results of the present study were found similar on the effects of direct exposure to non-thermal plasma on seedlings of crops like maize (Gutierrez-Leon et al. 2025) and barley (Benabderrahim et al. 2024). Among the effects include the development of longer and more extensive or branching root systems in addition to longer shoots which were promoted by non-thermal plasma (Wasko and Furno 2021). In metabolism, the same authors indicated that non-thermal plasma treatment increased protein and carbohydrate metabolism and increased chlorophyll production. Shah et al. (2023) also examined the effect of plasma using DBD in an Argon environment. In this study, they observed that there is increased growth rate in different parts of the Okra plant from treated seeds compared to untreated seeds. They explained that it is due to improved nutrient uptake and increased cell division and elongation due to seed alteration.

Further, plasma treatment was observed to affect phytohormones in plants. As reported by Sudhakar et al. (2011), plasma treatment stimulated cell division, elongation, and proliferation due to plasma affecting auxin and cytokinin. This was also reported by Perez Piza et al. (2018) in peas where they observed a decrease in Absciscic acid (ABA) and increase in Indole-3-acetic acid (IAA) which promotes increase in growth in plants. This can be observed on the increase in total biomass of both cv. 'Red Ruby' and cv. 'Green Smooth'. The significant difference in vigor index I incorporating both germination and seedling growth of untreated and APP treated seeds for the two varieties may be due to mechanical scarification and seed coat erosion caused by direct exposure of seeds to plasma. While seedlings emerging from treated seeds showed enhanced total biomass and plant height in both cultivars may be due to early stimulation of metabolic and enzymatic activity that promotes rapid cell division and elongation (Stolarik et al. 2015). Similar findings were reported by Dhayal et al. (2006) in *Carthamus*, Zhou et al. (2011) in tomato, by Jhifeng et al. (2014) in wheat and by Sera et al. (2011) in Poppy. This effect may be also attributed to increased seed mobilization and acceleration of the catabolism of seed nutrients making it available to the germinating seedling hence the improved growth. Additionally, Kumar et al. (2018) explained that the positive effects of plasma treatment is due to the removal of the lipid layer of the seed coat making the seed hydrophilic. In Okra, they observed that 12-min plasma treatment shortens the time to first fruit harvest. Among the other parameters include increased final harvest and higher seed yield per plant were explained by Kumar et al. (2018) to be caused by earlier seed emergence.

Plasma exposure can generate reactive oxygen and nitrogen species (RONS), which may act as signaling molecules that stimulate growth-related genes or hormonal responses (Waskow & Furno, 2021).

Enhanced root development could translate to improved nutrient and water uptake, contributing to the overall plant health and vigor.

Differential effects on two cultivars tested were only observed on majority of germination characteristics measured but were not observed on seedling characteristics. In terms of germination rates, varietal differences APP treatment was reported by Yodpitak et al. (2019) on rice where they observed that all rice varieties after plasma treatment had improvement on germination rate, root length, shoot length but their degree of improvement was variety dependent. Moreover, Ling et al. (2015) also observed that Zhongshuang 7 showed better response to plasma treatment than the other variety which is Zhongsuang 11. Difference in response to plasma treatment were also observed on quinoa (Gomez-Ramirez et al. 2017), *Arabidopsis thaliana* seeds on osmotic and saline stress (Bafail et al. 2019), and in beans (*Phaseolus vulgaris*) (Bormashenko et al. 2015).

The enhancement of APP treatment was observed to be consistent in germination characteristics and other seedling characteristics. Germination characteristics show variety dependent effects mostly in terms of the magnitude of the enhancement of germination vigor, time and shortened time. Further, in terms of seedling characteristics, APP treatment show consistent enhancement on and seedling characteristics have on total biomass, and other seedling parameters such as root and shoot lengths on two varieties of Okra tested in this study.

CONCLUSION AND RECOMMENDATIONS

This study shows that direct atmospheric pressure plasma treatment of Okra (*Abelmoschus esculentus*) significantly promoted germination and early seedling growth. APP-treated seeds showed improved germination percentage, higher germination rate index indicating more uniform germination, and faster germination time. SEM qualitative analysis showed evidence of seed coat erosion and microstructural changes that occurred in APP-treated seeds for both varieties. Alterations on the morphology of the seed coat may have promoted better and faster water uptake that triggered faster germination. Further, seedlings from APP-treated seeds also produced seedlings with higher total biomass, longer root, shoot and taller plants morphological traits on both cultivars being studied. APP treatment in two Okra varieties exhibited variety dependent effects on germination characteristics except germination percentage. While no variety dependent but consistent positive effects of APP treatment was observed for both cv. 'Red Ruby' and cv. 'Green Smooth'. The results affirm that APP treatment can serve as a sustainable, non-chemical pre-sowing seed treatment method for enhancing the germination and seedling vigor of Okra. Hence, is recommended as a seed treatment of Okra to improve its germination and seedling growth.

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