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Impact of Plasma-Activated Water on Germination and Growth of Basmati Rice

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Abstract. Basmati rice, renowned for its exceptional aroma, distinct flavor, and long grains, is a staple in global cuisines. Understanding and enhancing the germination and growth of Basmati rice seeds carry significant implications for both agricultural practices and culinary traditions. This study investigates how plasma-activated water, produced through atmospheric pressure air gliding arc discharge, affects Basmati rice seeds germination and growth parameters. The physiochemical analysis reveals a progressive increase in water acidity, electrical conductivity, oxidation-reduction potential, total dissolved solids, and nitrate/nitrite concentrations as treatment time extends from 0 to 20 minutes. The results highlight a significant impact of plasma-activated water on Basmati rice germination and seedling growth. The seed imbibition rate rises with longer plasma activation, reaching a peak at 10 minutes, leading to maximum seed germination, extended seedling shoots, and increased plant weight compared to the control group. However, prolonged exposure (20 minutes) shows adverse effects on seed germination and growth. These findings contribute valuable insights into the potential applications and limitations of plasma-activated water in Basmati rice.

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INTRODUCTION

In the past several years, researchers have been interested in the generation of atmospheric pressure non-thermal plasma for the production of plasma-activated water (PAW) due to its wide range of growing applications in diverse fields [1–6]. One of PAW's key uses is in agricultural seeds germination and seedling growth. PAW is generated by the unique transfer of chemical reactivity and energy from gaseous plasmas to water without adding other chemicals. This process results in water with notable, broad-spectrum biological activity due to its transient chemical species, such as nitrate and nitrite ions, which can enhance plant growth. Soaking seeds in PAW serves not only as an antibacterial treatment but also promotes seed germination and early plant growth. Additionally, PAW has potential applications in improving crop resilience against environmental stresses, including drought, which is critical in sustainable agriculture. These emerging plasma-based technologies aim to enhance agricultural productivity with minimal environmental impact, contributing to sustainable economic [4].

When PAW is sprayed on rice plants, it increases the concentrations of total carotene, chlorophyll, plant height, stem diameter, and dry weight. Additionally, the rice grains contents of sugar and total soluble protein were raised, and the germination yield increased [7]. Significant changes in functional groups associated with starch's capacity to bind water were observed by employing PAW [8]. The utilization of powdered sweet orange peel treated with PAW in the production of novel food products that are both functional and nutraceutical [9]. It might greatly enhance the physiological and biochemical characteristics of the basil plant [10]. With the least amount of fluctuation in nutritional and qualitative parameters, PAW enabled an average reduction of total mesophilic and psychrotrophic bacteria as well as Enterobacteriaceae washing [11]. PAW treatment is taken as an alternate technique that lowers the risk of deterioration and safety concerns while maintaining the quality of Korean rice cakes [12]. Enhancing the microbiological stability of steamed rice cakes is found with PAW treatment [13]. The combined effects of plasma seed treatment and PAW application improved the growth parameters of the plants; enzymatic activity enhancement improved the defense mechanisms of the plants; increased concentrations of total soluble protein and sugar were observed in the paddy grains; and, lastly, an increase in yield was noted [14]. Plasma comprising electrons, positive or negative ions, and neutral species can produce reactive oxygen and nitrogen species (RONS), which have antibacterial properties. When the rice seed was treated with O_2 - air glow discharge plasma and air-plasma activated water, the occurrence and severity of brown spots were significantly reduced [15]. Through water imbibition before sowing or seed decontamination during dry storage, plasma-activated water can be effectively used to create control measures for seed-borne fungal infections [16]. During the vegetative growth stage, plasma irradiation boosted grain production, panicle count, and seedling growth of rice. Treatment during the period of reproductive growth, on the other hand, had no effect or had a harmful effect [17]. Similarly, Basmati rice's functional qualities can be enhanced by the low-temperature plasma treatment [18]. When considering an increase in plasma power and treatment time, the cooking time was shortened but water up-taking properties considerably increased. According to water uptake kinetics, the reduction in rate constant in the plasma-treated samples indicated a faster cooking rate. Basmati rice can benefit from plasma treatment to enhance its cooking quality [19]. The properties of plasma-treated rice, including hydrophilicity, surface energy, cooking time, and hardness, showed a notable improvement [20].

In terms of production, consumption, and cultivated area, rice is the most important crop in Nepal, which accounts for one-fourth of the gross domestic product (GDP) and produces more than two-thirds of farm household income, has a direct impact on the economic progress of our nation [21]. Since ancient times, Nepal has been the origin of and center for the production of Basmati rice. Basmati rice is valued for its pleasant aroma, fineness, purity, sanctity, and nutritious content. It is also used for feasts, weddings, and other ceremonial ceremonies, as well as for decorating, fasting, and other purposes [22]. The application of plasma-activated water on Basmati rice for germination and seedling growth is still lacking. In this work, we have produced the atmospheric pressure gliding arc discharge to study the effect of plasma-activated water on Basmati rice seed's germination and growth parameters. The produced discharge is characterized via optical and electrical methods and finds the plasma density and electron temperature [23]. The physical and chemical properties of plasma-activated water have been studied for the different plasma exposure times of 0 to 20 minutes. The results showed that the 10-minute plasma-activated water significantly influences Basmati rice's germination characteristics and seedling growth.

MATERIALS AND METHODOLOGY

The experimental arrangement for producing and characterizing the atmospheric pressure gliding arc discharge and producing the plasma-activated water is shown in Fig. 1. The discharge is generated using a locally assembled power supply [24] at an airflow rate of 15.0 liter per minute (LPM). The voltage across gliding arc discharge

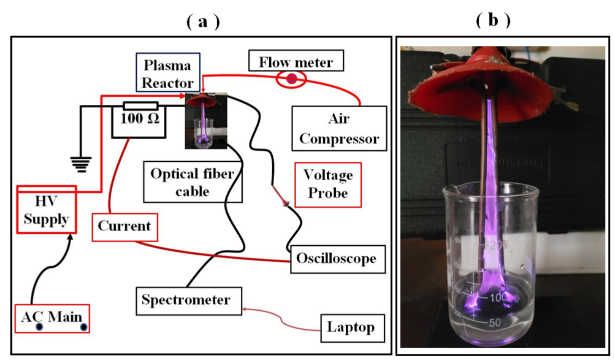

FIGURE 1. (a) Schematic block diagram for the generation of plasma-activated water from atmospheric pressure gliding arc discharge along with discharge characterization and (b) discharge and plasma-activated water produced in the laboratory.

is measured using a 1000 ×voltage probe PINTEK HVP-40 and an oscilloscope (Tektronix TBS 1052B). A 100 Ω resistor is connected in series with the ground (Tektronix TPP0051, 10× voltage probe) electrode to measure the discharge current. Optical emission spectroscopy of gliding arc is observed by using an HR1-high-resolution spectrometer (ASEQ Instrument) in which the optical fiber cable is placed 10.0 mm below the lowest point of the electrode. The obtained spectra are an average of 30 observations with 300 ms of integration time. Determination of plasma parameters such as electron temperature and density is essential for almost all plasma applications. The electron temperature (T_e) is determined by using the Boltzmann plot method [25] in which the produced plasma is considered as in local thermal equilibrium defined as:

$$\ln\left(\frac{\lambda_{ki} I_{ki}}{A_{ki} g_k}\right) = -\frac{E_k}{k_B T_e} + C \tag{1}$$

where I_{ki} is the intensity of transition from k to i state, λ_{ki} is the wavelength of transition, A_{ki} is the transition probability, g_k is the statistical weight, E_k is the upper energy level, T_e is the electron temperature, and C is the constant intercept of fitted straight line. As we plot the graph of $\ln\left(\frac{\lambda_{ki} I_{ki}}{A_{ki} g_k}\right)$ as the function energy E_k [26]. Once the discharge temperature is obtained, the plasma density is calculated from the Boltzmann-Saha equation [25]. The plasma-activated water is made below 10.0 mm from the lower point of the electrode by treating 40.0 mL of de-ionized water (Ocean Medico) with different treatment times 5, 10, 15, and 20 minutes, which are denoted by 5PAW, 10PAW, 15PAW, and 20PAW. On the other hand, 0 PAW represents the control de-ionized water (untreated). The reactive nitrogen species (RNS) nitrite and nitrate concentrations developed in water are measured by test stripes (Changchun MDC Medical Co., Ltd.). The percentage of hydrogen (pH), total dissolved solids (TDS), electrical conductivity (EC), and oxidation-reduction potential (ORP) are measured by the 7-in-1 RCYAGO water quality tester. The water quality tester is calibrated using the buffer solution having a pH of 9.18. The Basmati rice of three types (Khumal-12, khumal-14, and Khumal-16) seeds were collected from the Nepal Agriculture Research Center, Khumaltar, Nepal, and healthy and similar types of seeds were selected. From the selected seeds, thirty seeds are soaked in 0, 5, 10, 15, and 20 min PAW. The seeds were weighted and placed in separate Petri dishes for each experimental group and soaked in 40.0 mL of respective water. These soaked seeds are removed from the water and cleaned with tissue paper, and weight. The water uptaking rate by the seed is calculated as

$$\text{Water imbibition rate } (\%) = \frac{m_1 - m_0}{m_0} \times 100 \tag{2}$$

where m_1 is the weight of the seeds after soaking in water after 24 hrs and m_0 is the weight of the seed before soaking. The 10 seeds were planted in each plastic glass with 80 grams of a mixture of 50% soil, 25% Vermicompost (Argo Kranti, Nepal) with 7.41 pH, and 25 % sand. The planted seeds are kept in the window side of the room in an ambient environment and 10.0 mL of respective water is poured into a glass every two days. The temperature and humidity were in the range 5^{o} to 18^{o} C and 30 to 50% respectively of the environment. The germination rate is calculated as:

$$\text{Germination rate } (\%) = \frac{\text{Germination in 3 day}}{\text{Total number of seeds}} \times 100 \tag{3}$$

Root and shoot length is measured by regular scale having the least count of 0.1 cm. The fresh weight of the plant is weighted by digital weight balance (Daewoo Digital) having the least count of 0.001 gm. Our experiment included five replicates, and the data are presented as mean values with standard deviations. Fig. 2 displays the real picture of real working conditions and seedling growth of Basmati rice seeds after 21 days in plastic glasses.

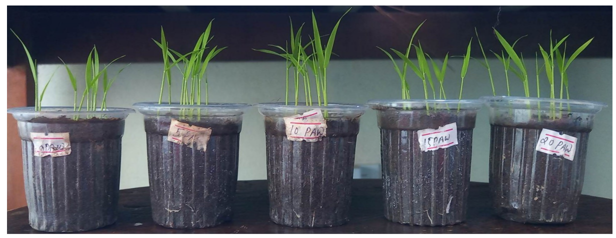

FIGURE 2. Seedling growth of Basmati rice plant in a plastic glass after 21 days.

RESULTS AND DISCUSSION

Electrical and Optical Characterization of Discharge

The current-voltage characteristics, optical emission spectra of the atmospheric pressure air gliding arc discharge, and Boltzmann plot for calculation of the electron excitation temperature of the discharge are depicted in Fig. 3. The plasma is produced with a peak-peak discharge voltage of 15.40 kV DC and a discharge current of 141.60 mA, depicted in Fig. 3(a). The selected voltage and airflow rate optimized the stability and intensity of the discharge. The obtained emission spectra of air gliding discharge with the presence of different active species are shown in Fig. 3(b). The second positive system (SPS) of nitrogen species is observed in the wave band 310-380 nm, whereas the first negative system of nitrogen species is observed in the 390-440 nm wave band. Moreover, the hydroxide radical OH is observed at 309 nm in the spectrum of the gliding arc discharge which plays a crucial role in plasma chemical reactions. The nitric oxide gamma band NO_γ is also observed in the spectrum of discharge in the wave band 200 to 280 nm [27]. The obtained graph for the Boltzmann plot and linear fit is depicted in Fig. 3(c). When we take the reciprocal of slope from linear fit, we can find the electron temperature of the produced arc discharge which is obtained as 1.25 eV. With this obtained electron temperature, the density of electrons is found to be 9.26×10^{16} cm^{-3}.

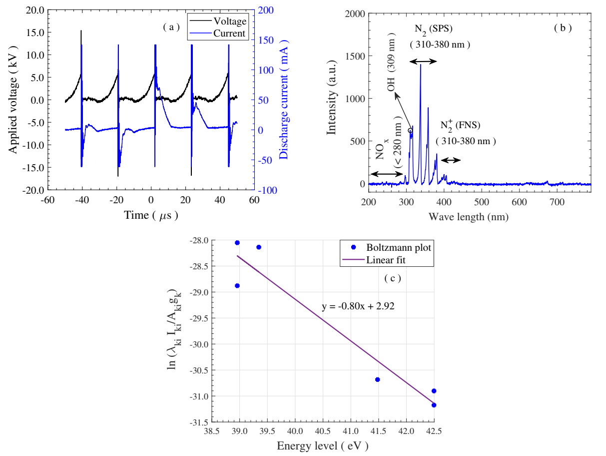

FIGURE 3. (a) Real-time voltage–current waveform, (b) optical emission spectroscopy spectra, and (c) Boltzmann plot of atmospheric pressure air gliding arc discharge plasma.

Physio-chemical properties of PAW

The physicochemical properties of water; pH, TDS, EC, ORP, temperature, nitrate, and nitrite concentration are shown in Fig. 4. It has been observed that the pH of water exhibits a decreasing trend with increasing activation time from (6.73 ± 0.20) at 0 minutes to (4.97 ± 0.16) at 20 minutes. TDS, EC, ORP, Temperature, nitrate, and nitrite concentrations, on the other hand, increase as the activation time increases from 0 to 20 minutes. The TDS increased from 0 to (67 ± 6) ppm as the activation time increased from 0 to 20 minutes, EC increased in a similar trend from 0 to $(134 \pm 12)\,\mu$S/cm while ORP increased from (376 ± 30) to (464 ± 19) mV which is a 23.4 % increase. The temperature also increased with every increment in activation time starting at (58.6 ± 2.4) F and increasing by 12.6 % to become (65.9 ± 2.1) F at 20 minutes of activation. With increasing activation time, both nitrate and nitrite concentrations increased. Nitrate increased from 20 mg/L at the start to 250 mg/L after 15 minutes of activation, where it remained till 20 minutes of activation. Nitrite, on the other hand, increased from 0 mg/L in untreated water to 40 mg/L in 20 minutes treated PAW. The observed phenomena can be attributed to the introduction of reactive oxygen and nitrogen species. These reactive species are formed when the plasma discharge interacts with the surrounding air [28]. Because atmospheric air is used as the feeder gas, the discharge process involves the presence of nitrogen and oxygen species. Under the influence of high voltage, these species ionize and become soluble in water, contributing to the observed trends in the measured values.

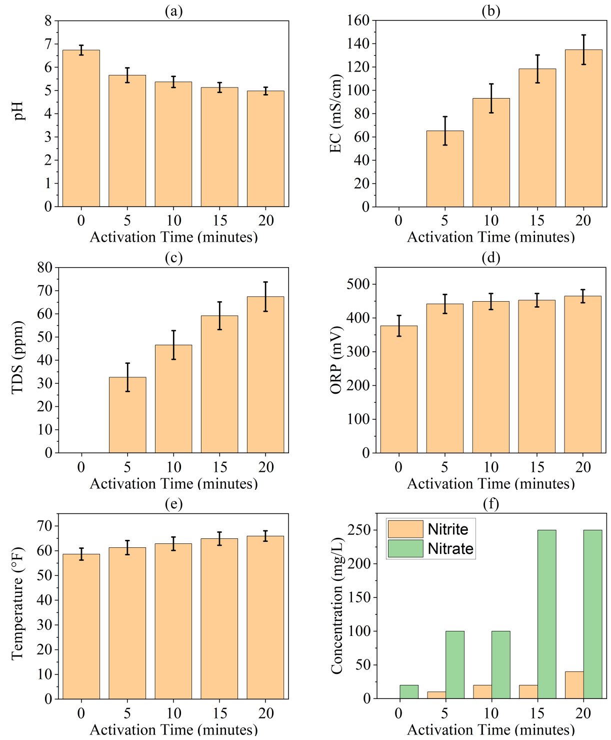

FIGURE 4. The variation of physio-chemical parameters of PAW for different treatment times (a) pH, (b) EC, (c) TDS, (d) ORP, (e) temperature, and (f) nitrite and nitrate concentrations.

Water Imbibition Rate

The water imbibition rates of Basmati rice seeds in different PAW for different soaking times are demonstrated in Fig. 5. Specifically, increasing the plasma activation period from 0 to 15 minutes increased the seeds water imbibition rate while a decrease was seen when the treatment time was lengthened to 20 minutes. In all samples, the highest water imbibition rate after 8 hours of soaking in water was seen in the group containing 10 minutes PAW. In Khumal-14, the water imbibition rate of the 10 PAW group was found to be $(22.8 \pm 1.6)\%$ which is an 11.8% increment when compared to the control group which had a water imbibition rate of $(20.4 \pm 1.1)\%$. The seeds of Khumal-16 had the highest water imbibition rate in 10 PAW too, with the average value of $(12.5 \pm 0.6)\%$ which is an increment of 30.1% from the control group which had a water imbibition rate of $(9.7 \pm 0.6)\%$. The seeds of Khumal-12 followed a similar pattern with the highest water imbibition rate as $(16.8 \pm 0.9)\%$ in the 10 PAW group which is an increment of 6.3% when compared with the control group which had water imbibition rate of $(15.8 \pm 0.8)\%$.

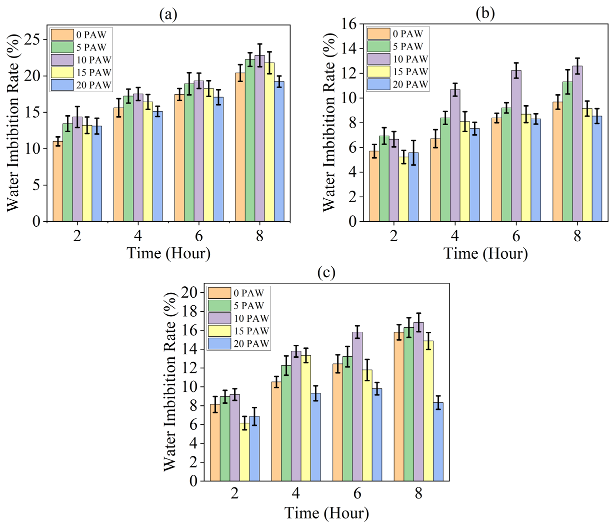

FIGURE 5. Water imbibition rate of (a) Khumal-14, (b) Khumal-16, and (c) Khumal-12 soaked in different activation times of plasma-activated water.

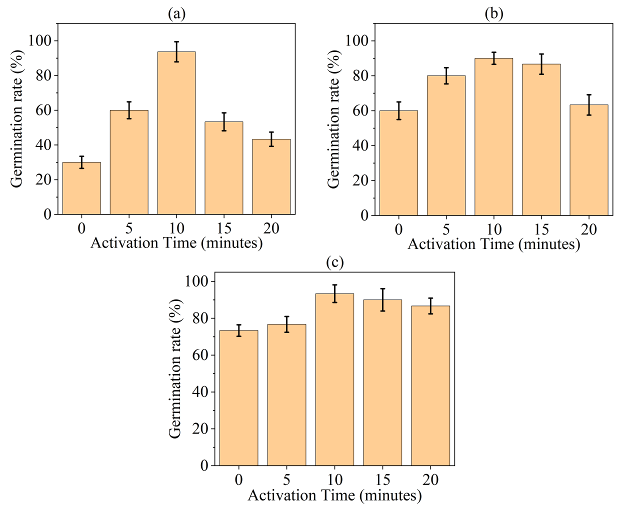

FIGURE 6. Germination rate after 3 days of plantation of (a) Khumal-14 (b) Khumal-16 (c) Khumal-12 rice seeds.

Germination

The germination rate of Basmati rice noted after 3 days of plantation is presented in Fig. 6. In all 3 samples, the germination rate was recorded as highest for the 10 PAW group. In Khumal-14, the germination rate of the 10 PAW group was recorded as $(93.7 \pm 5.8)\%$ which is 212.3% increment from the germination rate of a control group which was recorded as $(30.0 \pm 3.4)\%$. Similarly, in Khumal-16 the 10 PAW group had the highest germination rate of $(90.0 \pm 3.4)\%$ which is 50% higher than the rate of the control group recorded as $(60.0 \pm 5.1)\%$. Khumal-12 followed a similar pattern with the highest germination rate in the 10 PAW group. Thus significant improvement in the germination rate of PAW-supplied samples is observed.

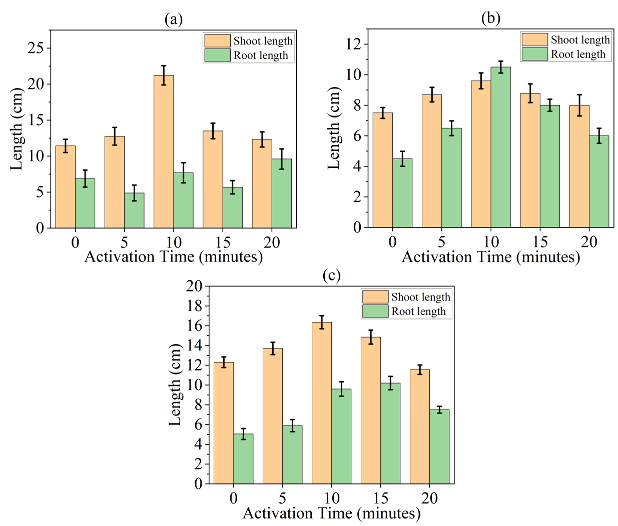

FIGURE 7. Shoot and root length of (a) Khumal-14, (b) Khumal-16, and (c) Khumal-12 rice seedlings recorded after 21 days of plantation.

Growth Parameters

The average root and shoot length of the Basmati rice plant in different plasma activation times of water after 21 days are presented in Fig. 7. The pattern in root length, however, was not consistent. In all 3 varieties of Basmati rice seeds, seedlings treated with 10 PAW recorded the highest shoot length. In Khumal-14, the 10 PAW group demonstrated average shoot length of (21.2 ± 1.3) cm which is 85.9% higher than the shoot length demonstrated by control group i:e (11.4 ± 0.9) cm. 10 PAW group had highest shoot length in Khumal-16 too, with value of (9.6 ± 0.5) cm while the control group demonstrated shoot length of (7.5 ± 0.3) cm. In the case of Khumal-12, the shoot length of the 10 PAW group was 33.3% higher than that of the control. The shoot length for the 10 PAW group and control were recorded as (16.4 ± 0.6) cm and (12.3 ± 0.5) cm respectively. The pattern in root length was not consistent but all samples had the highest root length in treated samples. Khumal-14 variety of seeds demonstrated the longest root length in the 20 PAW group, Khumal-16 in the 10 PAW group while Khumal-12 demonstrated the longest root in the 15 PAW group. The root length of the control group in Khumal-14 was recorded to be (6.8 ± 1.2) cm while the 20 PAW group had (9.6 ± 1.4) cm which is a 41.18% increment. In Khumal-16, the difference was notable with the con-

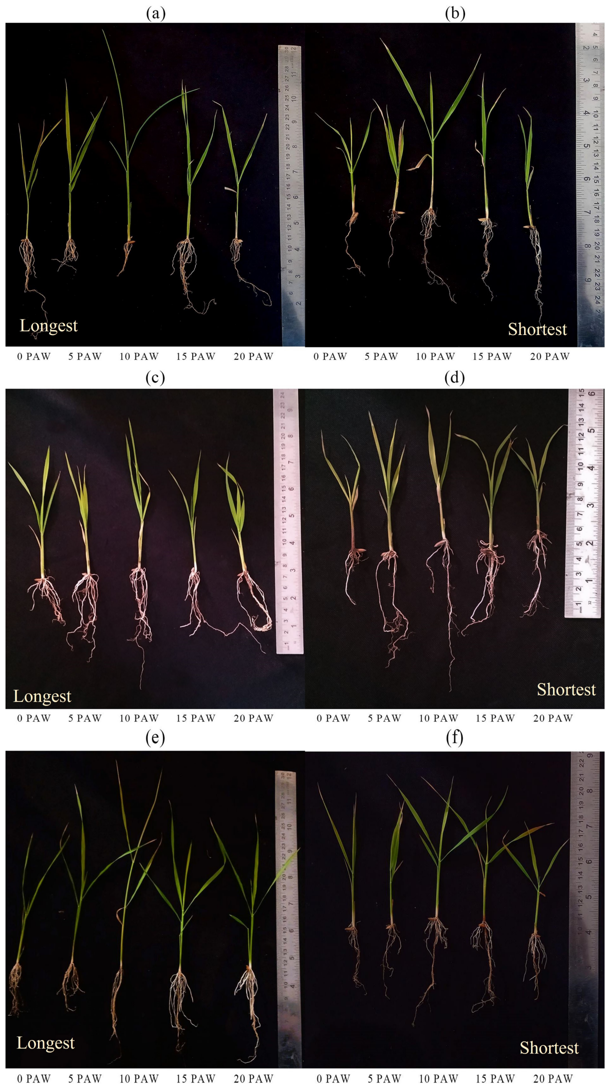

FIGURE 8. Longest and shortest shoots of every group; (a) and (b) of Khumal-14, (c) and (d) of Khumal-16, and (e) and (f) of Khumal-12 rice seedlings for all treatment times after 21 days.

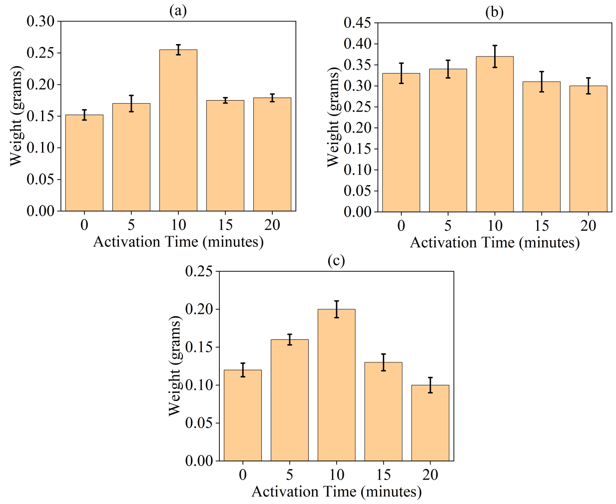

FIGURE 9. Average weight per plant recorded after 21 days of plantation in plastic cups of (a) Khumal-14 (b) Khumal-16 (c) Khumal-12 rice paddy seeds.

trol having (3.8 ± 0.5) cm while the 10 PAW group had a root length of (10.5 ± 0.4) cm which is a 133.3% increment. Khumal-12 variety of seeds demonstrated the longest root length on the 15 PAW group with (10.2 ± 0.7) cm while the control had a root length of (5.0 ± 0.6) cm. Thus, in the case of Khumal-12, the 15 PAW group had 104% longer root length when compared with the control. The longest and shortest length of the Basmati rice plant of each group is shown in the real picture in Fig. 8. It is observed that the seedling growth of the plant is highest in the longest and shortest category in 10 min plasma treated water used plant. These weights per plant recorded after 21 days of plantation in the cup are depicted in Fig. 9. In all 3 Basmati rice varieties, the 10 PAW group was recorded with the highest average weight per plant value. In Khumal-14, the control group weighted (0.152 ± 0.008) grams whereas the 10 PAW group had the weight of (0.255 ± 0.007) grams, which is a 33.3% increment. In Khumal-16, the control group weighted (0.330 ± 0.024) grams while the 10 PAW group had (0.370 ± 0.026) grams which is a 12.1% increment. Khumal-16 group followed a similar pattern with the control group having (0.120 ± 0.009) gram whereas the 10 PAW group demonstrated (0.201 ± 0.011) gram which is a 67.5% increase.

CONCLUSION

The study underscores the potential advantages of employing Plasma-Activated Water (PAW) in paddy crop cultivation, particularly in its influence on the germination and development of Basmati rice. The findings demonstrate that the PAW treatment, specifically the 10-minute exposure (10PAW), positively affected the germination of Basmati rice paddy seeds and the subsequent growth of seedlings. This resulted in accelerated seedling growth and higher germination rates compared to the control group. The observed enhancements in germination and seedling growth are likely attributed to the production of RONS by the activated water. The seedlings treated with 10PAW exhibited a notable 66.7% increase in weight compared to the control group. Furthermore, when contrasted with control seeds, those treated with plasma-activated water displayed superior germination, longer root and shoot lengths, and higher overall weight. However, it is important to note that an extended exposure of 20 minutes to plasma discharges negatively impacted the germination and development properties of rice paddy seeds. This highlights the significance of optimizing exposure times for realizing the positive effects of PAW on Basmati rice cultivation.

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EDITORS' NOTE

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