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Article

Plasma Activated Soil: A Novel Technique for Agricultural Soil Enhancement

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Abstract. In this work, the influence of atmospheric-pressure air plasma on soil quality improvement has been studied. The practical plasma model has been designed to shape like a rake using spark plugs. The high-frequency AC high voltage has been varied at 9, 12, and 15 kV for plasma generation. The soil has been treated directly with air plasma for three consecutive days with a discharge time of 15 and 30 minutes once a day before using it for cultivation. Regarding the experimental results, air plasma significantly positively affects soil enhancement. The germination rate and length of the sprout of all the morning glory seeds cultivated in the plasma-treated soils have been higher than the one of the control group, which are up to 1.74, and 1.14 times higher than that of the control group, respectively. From the soil analysis, the Total Kjeldahl Nitrogen (TKN) content could be improved for all the plasma-treated cases. The best condition has been at 12 kV with a discharge time of 15 minutes, where the TKN has been 4.33 times greater than the one of the control group. Moreover, the pH of all the plasma-treated cases has tended to increase, resulting in more pH-balanced soils.

Keywords: Atmospheric-pressure plasma, air plasma, morning glory, soil improvement.

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1. Introduction

Undeniably, the soil is an indispensable food source and agricultural industry. However, the problems of polluted and wasted soil have increased year by year due to both natural and human impacts. Some examples of natural impacts on soil are floods, wildfires, volcanic eruptions, cold and heat waves, earthquakes, and others. On the other hand, human impacts on wasted soil are mostly from a lack of awareness of waste disposal and agricultural fertilizing. [1]–[3]. Expanding industrial factories into the agricultural area could majorly influence the soil quality in those areas depending on the quality of chemical waste and wastewater management. Another main reason causing wasted soil is the long-term use of chemical fertilizers and pesticides, which causes an accumulation of the chemical residues and their by-products in soil, which could contribute to air and water pollution [4], [5]. These aforementioned issues have played an important role in soil health degradation, resulting in the reduction of productivity in agricultural activities. The important parameters that could indicate soil health are organic and inorganic matter content, pH, gas and water infiltration, topsoil depth, leachable salts (NO_3), and others [2], [5]–[9].

Nowadays, several treatment techniques have been proposed for soil quality improvements, such as physical treatment, biological treatment, and chemical treatment [10], [11]. One of the most novel green technology for soil treatment is the atmospheric non-thermal plasma (ANTP) technology [7], [11]–[14]. Recently, ANTP has become widely attractive in many eco-friendly and thermal-sensitive applications, such as surface modification, microbial inactivation, medical treatment, germination and growth stimulation of plant seeds, and wasted air, water, and soil treatment [7], [12]–[25]. During plasma generation, various useful physical and chemical processes are generated, such as neutral, ionized, excited states of atoms and molecules, photons, electric fields, electromagnetic wave radiations (ultraviolet and X-rays), shock waves, sputter etching, and chemical reactions. However, the most unique and notable property of ANTP is non-equilibrium advance oxidation processes (AOPs) at room temperature.

Regarding the AOPs of ANTP, various reactive species are essential in agricultural, biocidal, and antimicrobial activities, such as reactive oxygen and nitrogen species (ROS and RNS). Some outstanding reactive species and their by-products are atomic oxygen (O), ozone (O_3), hydrogen peroxide (H_2O_2), nitric oxide (NO), peroxynitrite ($ONOO^-$), nitrites (NO_2^-), and nitrates (NO_3^-), hydroxyl (OH•), hydrogen (H•) and oxygen (O•) radicals). O_3 and H_2O_2 have played a major role in microbial inactivation activities. NO_2^- and NO_3^- are the alternate source of nitrogen fertilizers, while OH• and H• have contributed to acid-base properties [7], [12], [15]–[19], [26]–[32]. It has been reported that H• and O_3 could enhance the decomposition of chemical residues in the soil, such as chloramphenicol (CAP), pentachlorophenol (PCP), and p-nitrophenol (PNP), [7], [15], [30], [33].

In this research, ANTP has been proposed to enhance soil quality for agronomy. Generally, three favorable ANTP models, which have been used to study the influence of plasma on soil improvement, are dielectric barrier discharge (DBD) [34]–[36], non-thermal gliding arc discharges [12], [37], and corona discharges [21], [24], [25], [38]. In this work, the ANTP model has been designed to resemble a rake-like using a spark plug as an anode, which could be practically applied for small farm tillage. The ANTP-generated spark plug is expected to instantaneously free capital chemically produced and stimulated for soil enhancement during the treatment. The useful radical species generated during the treatment have been expected to react, diffuse, and penetrate the treating soil. The plasma generated by the spark plug at this time seems to be classified in the corona discharge type [39]. Normally, the spark plug is used in a gasoline engine by a spark discharge in order to ignite the compressed air-fuel mixture in the combustion chamber [40]. Therefore, it would enable air plasma generation at atmospheric pressure easily. Moreover, the physical preference and its insulating material have led it to be suitably adopted and attached to the rack legs. The influence of ANTP on soil improvement will be studied by treating the target soils with ANTP before using it for morning glory seed cultivation. Various treating times and applied source voltages have been experimentally conducted in order to investigate the effects on soil enhancement. Plasma and its electrical and optical emission spectra characteristics have been observed. The plasma-treated soils analyzed have been pH, and the Total Kjeldahl Nitrogen (TKN). In addition, the growth parameters, i.e., the germination rate, the stem length, and the dry weight of morning glory cultivated in plasma-treated soil, have also been investigated.

2. Experimental Methods

2.1. Model and Experimental Setup

The schematic drawing of a spark plug plasma generator (SPPG) and the experimental setup for soil treatment is presented in Fig. 1. SPPG has been designed to have a shape like a rake with three legs. A spark plug (NGK 5111 BP7HS, a resistor-free standard spark plug), whose ground electrode has been cut, has been attached to each leg of the rake. At the end of the prongs of the rake, it has been covered by a dielectric material. The distance between the tip of the dielectric cap and the spark plug center of the electrode has been 8 mm. The terminals of each spark plug have been connected to the custom-made AC high-voltage power supply using an old TV fly-back transformer. The AC power source could supply high voltage of up to 15 kV at a frequency of 15 kHz. The copper ground plate has been placed under the treating soil. Therefore, the surface of the treating soil has acted as a cathode of SPPG.

The electrical discharge characteristics of discharge voltage (V_d) and current (I_d) have been investigated by an oscilloscope (SIGLENT, SDS2304). A high voltage probe (Pintek HVP-28HF) has been connected across the spark plug terminal and ground copper plate in order to observe the V_d waveform. The voltage drop across the 3.3 Ω monitor resistor has been reflected in the I_d waveform. The optical emission spectroscopy (OES) during plasma generation has also been investigated by a CCD spectrometer (Newport 71SI00087). The tip of the optical fiber detector has been located perpendicularly, far from the center electrode of the spark plug, for 1 cm.

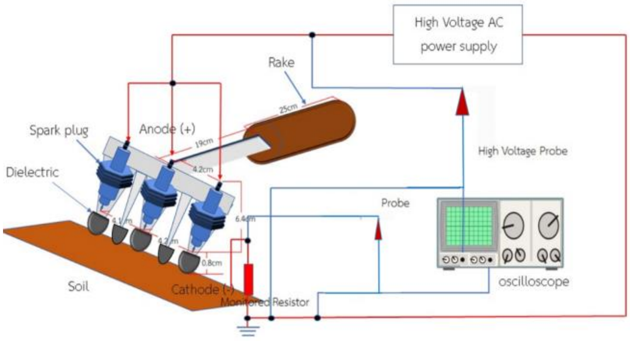

Fig. 1. The schematic drawing of experimental setup for a spark plug plasma.

2.2. Soil Treatment and Characteristics Analysis

2.2.1. Soil preparation and plasma treatment

The visually homogeneous loamy soils have been collected from the farming plot in Srinakharinwirot University, Ongkarak district, Nakornnayok, Thailand. Two kilograms of prepared soil have been put into the prepared 60×60×15 cm^3 cultivation plot. The prepared soils in the cultivation plot have been dried in the sun for seven days before the experiments.

In order to study the influence of plasma on soil improvement, the cultivation plot contained with the prepared soils have been moved to the suitable cultivating area (under the sunshade net), and then plasma-treated at different supplied voltages (0 (control group), 9, 12 and 15 kV), and treatment times (15 and 30 min). 250 mL of tap water have been uniformly sprayed over each plot once a day before the experiment for 3 h. The average ambient soil temperature before treatment was around 27 ^{o}C. The anode of SPPG during the treatment has been above the soil surface for 4 cm, approximately. The dielectric caps covering the legs of the rake have been immersed in the treating soil. Therefore, the treating soil surface has been broken down during the treatment process. In order to obtain the most uniform plasma treatment over the target soil, SPPG has been moved in a raster scan pattern over all the treating soil with a velocity of around 2 cm/s. The treating soil has been thoroughly ploughed-up every 5 min. The treatment process has been operated until meeting the goal of each experiment. For the control group, the treatment process has been the same as the one of the plasma-treated case but without the supply of high voltage. The soils have been plasma-treated once a day for three consecutive days. After 3 days of plasma treatment, the process has been completed, the soils have been sampled for characteristic analysis, and used for Chinese morning glory seed cultivation in the next consecutive day. All the experiments have been repeated thrice for statistical analysis.

2.2.2. Acid-base (pH) and soil humidity

Fifty grams of 1:1 examined soil and distilled water have been homogeneously mixed with 50 mL distilled water before leaving it precipitating for 30 min. Then the samples have been pH measured by a pH meter (METTLER TOLEDO, SevenEasy™ pH). The average soil humidity has been monitored by a humidity probe (Yieryi, Soil pH-moisture analog meter).

2.2.3. Total Kjeldahl Nitrogen (TKN)

The Total Kjeldahl Nitrogen (TKN) or the sum of free ammonia and organic nitrogen compounds (%Nitrogen) in soil has been performed according to the Standard Methods for Examination of Water and Wastewater by Kjeldahl method [41], [42].

2.3. Seedling Growth Measurement and Statistical Analysis

2.3.1. Seed preparation

Chinese morning glory (*Ipomoea aquatica*) seeds have been purchased from East-West seed, Sorn Dang brand, Lot. No.1907:339. Defect-free seeds have been visually examined and used for the study.

2.3.2. Seedling growth measurement

The Chinese morning glory seeds have been soaked in tap water for 24 h before cultivation. In each cultivation plot, fifty seeds have been cultivated in different plasma-treated soil conditions in the open environment in the middle of March. The average ambient temperature and relative humidity were around 31 ^{o}C and 72%, respectively. Each plot has been sprayed with 500 mL of tap water twice a day (9 AM and 4 PM). The seed germination rate has been observed after 12, 36, 40, and 64 h after cultivation. The growth rate of the Chinese morning glory sprouts has been investigated by the average length of the plant after cultivation for 6, 7, 8, and 9 days. The average dry weight of sprouts has been measured after cultivation for 9 days. The sprouts have been dehydrated in the universal oven (Memmert Germany; Model: UN) at 105° Celsius temperature for 4 h before weighing by an analytical balance (Sartorius; Model: BSA2245-CW).

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2.4. Statistical Analysis

All the experimental results have been statistically analyzed by an analysis of variance test (One-way ANOVA) with significant differences among samples at $p<0.05$.

3. Results

3.1. Spark Plug Plasma Characteristics

After the source voltage (Vs) has been supplied to the spark plug plasma generator (SPPG) with the optimal cathode gap length, air plasma has been generated between the tips of spark plug electrodes and the counter electrode (target soil) as shown in Fig. 2. The plasma characteristic looked like a streamer air corona discharge, which has been randomly moved over the rough surface of the treating soil. The plasma streamer length generated from each spark plug has been around 4-10 mm far from the spark plug tip. The intensity and the streamers of plasma have increased with the higher supplied voltages.

Fig. 2. Air plasma generate from the designed device for soil treatment.

The electrical characteristics of SPPG are depicted in Fig. 3 and 4. An example of the comparison between the voltage waveforms with no load and load (soil treatment) at the 12 kV-supplied voltage is illustrated in Fig. 3a). The breakdown voltage with soil load has happened around 3.5 kV. The disappearance of 8.5 kV of supplied voltage has contributed to plasma generation. It should be mentioned that a slight phase shift of the voltage waveform would come from load impedance. Fig. 3b) presents the comparison between the discharge voltage waveforms of plasma generation with different cathode types at the same electrode gap distance (4 cm). It could be noticed that the breakdown voltage for the case of the copper plate electrode had lower voltage than the one of the soil electrode case by 1.5 times, approximately. This is because the electrical conductivity of copper is greatly higher than the one of the soil, resulting in gas breakdown mechanism enhancement.

The comparison of the electrical characteristics (discharge voltage and current) of SPPG generation at the different supplied voltage is illustrated in Fig. 4. The discharge current peaks have been around 0.03, 0.037, and 0.49 A at 9, 12, and 15 kV of supplied voltage, respectively. It could be noticed that the discharge voltage and current have increased as the supplied voltage has been increased. From the above-mentioned, it could be implied that the discharge has been in the abnormal glow region [21]. Therefore, a slight increase in soil temperature during the plasma treatment could be noticed. However, the temperature at the highest supplied voltage has increased from the ambient soil temperature to 38°, and 49° Celsius after 15-, and 30-min plasma treatment, respectively. The accumulation of heat in the treated soil would be from a thermionic emission effect in the abnormal glow discharge regime, and the difficulty of thermal diffusion among soil grains to the ambient temperature. Moreover, the joule heating caused by discharge current flowing through the treated soil during plasma treatment would also contribute to heat accumulation.

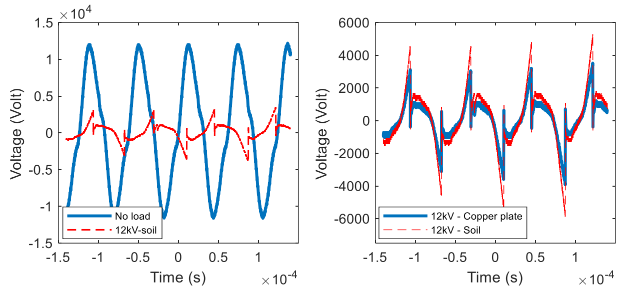


Fig. 3. Comparison of voltage waveform characteristics at 12 kV supplied voltage with the gap distance of 4 mm between a) no-load and soil load (electrode), and b) copper plate and soil electrode.

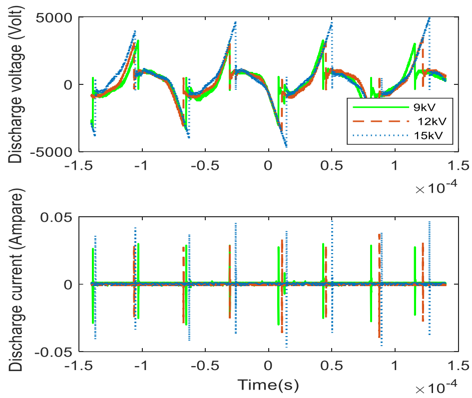


Fig. 4. Discharge voltage and current characteristics during soil treatment at different supplied voltages.

The optical emission spectra (OES) during the soil treatment at different supplied voltages are depicted in Fig. 5. It could be noticed that the OES characteristics of every condition have the same trend; however, the intensity is different. The dominant hydroxide (OH^-) emission spectra (306-315 nm), hydrogen emission line H_α (656.3 nm) [43], and atomic oxygen lines (777 and 844 nm) have been observed [44]. Moreover, prominent peaks between 300−470 nm of N_2 excited species have been detected. In this range, there are two main two systems of N_2 second positive system, which are excited molecular nitrogen (N_2*), and the molecular nitrogen ions (N_2^+) in the range of 300–390, and 390–480 nm, respectively [24], [45]. These radicals have an essential role in various reactive nitrogen and oxygen species (RNS and ROS) productions, as mentioned in the introduction part, which are beneficial in bio, medical, and agricultural applications [15], [17], [18], [21], [24], [45].

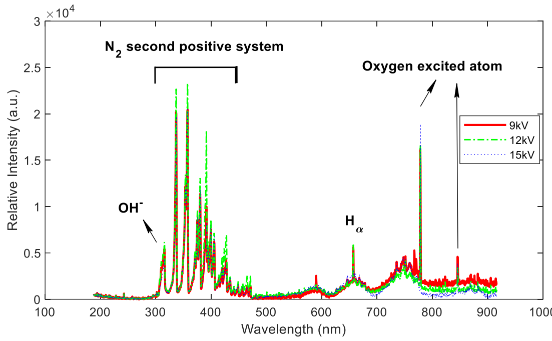


Fig. 5. OES of air plasma during the soil treatment.

3.2. Influence of Plasma-Treated Soil on Morning Glory Growth

After the source voltage has been supplied to the spark plug plasma generator with the optimal cathode gap length, air plasma has been generated between the tips of the spark plug electrodes and the counter electrode (target soil) as shown in Fig. 2. The plasma characteristic looked like a streamer air corona discharge, which has been randomly moved over the rough surface of the treating soil. The plasma streamer length generated from each spark plug has been around 4-10 mm far from the spark plug tip. The intensity and the streamers of plasma have increased with the higher supplied voltages.

After the treatment process has been completed, the influence of plasma-treated soil on morning glory growth has been studied. Three indicators of plant growth, which have been seed germinations, length of sprouts, and weight of sprouts, have been investigated.

3.2.1. Seed germinations

After the morning glory seeds have been planted in the planting plot, the germination rate of the seeds has been monitored. Fig. 6a) presents the germination rate of morning glory seeds monitored for 64 h after planting. It could be seen clearly that the germination rates of the seed planted in plasma-treated soil have a higher rate compared with the ones of the control group. The higher germination rate has been found in the plasma-treated soil at 12 kV, 15 min, and 15 kV, 15 min, which has been about 94 percent. However, the germination rate in the case of 15kV, 15 min treatment, has saturated the fastest at the highest germination rate. In this case, the germination has reached 90 percent after 36-h cultivation, which is 2.65 times of the control group.

3.2.2. Length of sprouts

Figure 6b) presents the average length of the morning glory sprout. An example of a planting plot of morning glory sprouts in each experimental condition after 9 cultivation days is presented in Fig. 7. It can be seen that every morning glory planted in the plasma-treated soils (MGPPTS) condition has a longer average sprout length than the one of the control group. The longest sprout length has been found in the case of 12 kV, 15 min plasma treatment, which is 1.87 cm longer than the average length of the control group. In the case of 15 kV, 30 min plasma treatment, which had the highest germination rate condition, its average length has been slightly shorter than that of 12 kV, 15 min plasma treatment, around 0.33 cm.

Regarding the statistical analysis with the 0.05 p-values, it could be confirmed that the average length of all the plasma-treated conditions, except for 9 kV treatment, has been significantly different from the one of the control group. This could mean that plasma has a significant influence on sprout length.

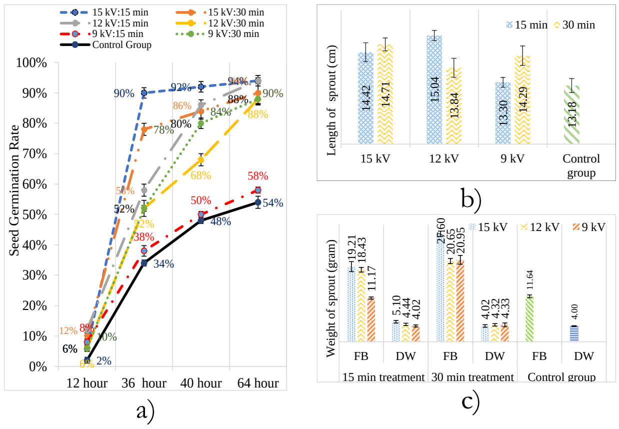


Fig. 6. a) Germination rate of morning glory seeds, b) length of sprout, and c) weight of sprout at various conditions.

3.2.3. Weight of sprouts

After 9 days of cultivation, the morning glory sprouts of every experimental condition have been weighed. Figure 6c) illustrates the comparison between the fresh (FW) and the dried weighs (DW) sprouts under various conditions. It could be noticed that MGPPTS at 12 kV and 15 kV have greater FW than the one of the control group, except for the 9 kV plasma treatment, which had a similar FW to the control group. However, DW of MGPPTS has been just slightly higher than that of the control group, which has been 4.23 g, approximately.

3.3. Soil Characteristics Analysis

A basic soil characteristics analysis, i.e., acid-base, soil humidity, and Total Kjeldahl Nitrogen, has been done after the treatment process. The analyzing results are as follows.

3.3.1. Acid-base (pH) and soil humidity

Acid-base or pH is a fundamental indicator reflecting the soil quality [20], [34]. Normally, the optimum soil pH for planting ranges from 5.5 to 7.5. However, many plants are suitable for a pH value outside of this pH range. This time, the pH of the plasma-treated soil pH could be

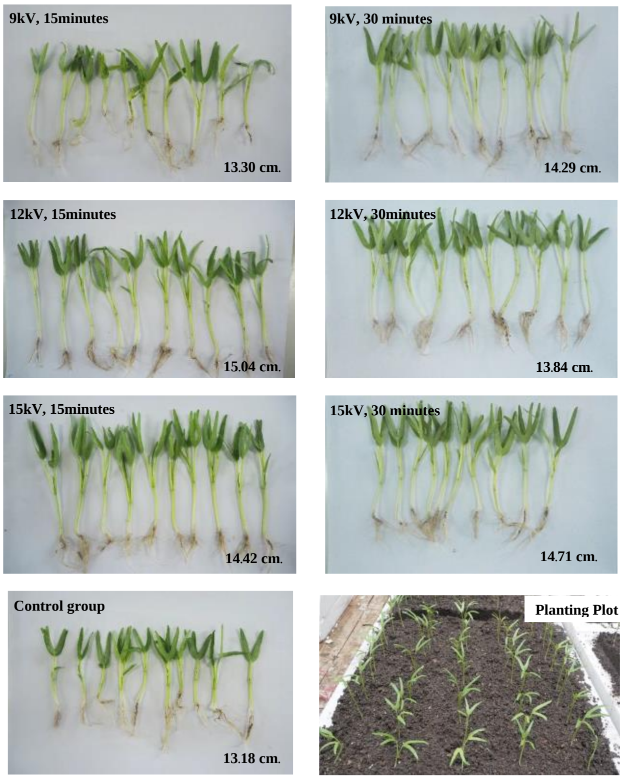


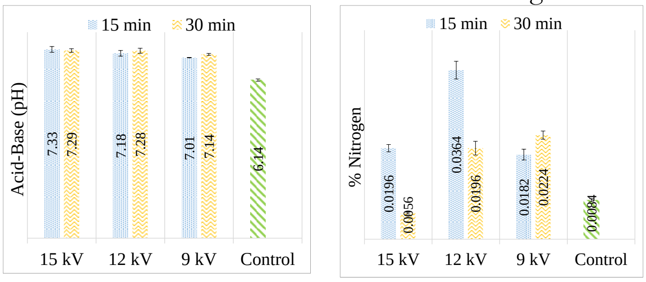
Fig. 7. Example image of planting plots, and morning glory sprouts in each experimental condition after 9 cultivation days. The inset number is the averaged sprout length.

increased from 6.14 (pH of the control group) up to 7.33 in the case of 15 kV, 15 min treatment, as shown in Fig. 8a). The pH of each plasma-treated soil has not been quite different. The average pH has been approximately 7.20. This could imply that the pH of the plasma-treated soil has become more balanced after plasma treatment.

The soil humidity was measured before and after the plasma treatment. The average soil humidity of the control group before and after being sprayed with 250 mL tap water was around below 10 %, and 21 %, respectively. Regarding the heat accumulation in the plasma-treated soil during treatment, the soil humidity had slightly decreased. At the highest soil temperature (49° Celsius), the soil humidity was approximately 20 %. However, it should be noted that this soil humidity was the one before the cultivation process. During the cultivation period, the soil humidity has been around 61 % according to the more water sprayed on the cultivation plot and the sunshade net.

3.3.2. Total Kjeldahl Nitrogen (TKN)

TKN in the soil represents the amount of nitrogen in the soil (%Nitrogen) in the forms of total organic nitrogen and ammonia [42], which plays an essential role in plant growth. From the analyzing results, it could be noticed that the TKNs of plasma-treated soils have tended to increase after plasma treatment with the optimal treatment time and supplied voltage. It can be seen that TKN has increased when the soil has been treated with high



a) b)

Fig. 8. a) acid-base, and b) Total Kjeldahl Nitrogen (%Nitrogen) in soils from various conditions.

supplied voltage and short treatment time (15 min) for the case of 12 and 15 kV-supplied voltage as shown in Fig. 8b). The TKN could be increased up to 4.33, and 2.33 times higher than the one of the control group. However, the TKNs of both these conditions have declined after an increase in treatment time. This is in contrast to the case of the 9 kV supplied source voltage, whose TKN has increased with treatment time.

4. Discussions

Regarding the experimental results and the statistical analysis, it could be confirmed that air plasma generated by the proposed spark plug plasma generator (SPPG) could enrich the treated soils, resulting in the stimulation of morning glory planted in the plasma-treated soils (MGPPTS) growth. The germination rate could be improved at the rather high supplied voltages. The MGPPTS could grow with a longer average length than the one of the control group. Moreover, they had a heavier FW. However, the DW has been just slightly heavier than the one of the control group. This can imply that the MGPPTS could absorb water from the plasma-treated soil better.

The interactions mechanism of chemical species generated during air plasma generations with treated soils could be divided into 3 main phases, similar to the mechanism of plasma–liquid interaction, which are the gas phase, the gas-soil interface phase, and the bulk soil phase [11], [18], [36], [46]. In the bulk soil phase, the physical appearance of the soil has a strong influence on the chemical chain reaction. The radical species have been mostly generated in the gas and gas-soil interface phases since plasma has been directly in contact with the target. Conversely, the reaction in the third phase is rather complex since the bulk soil is not homogeneous compared to the liquid phase. Humidity (H_2O) has played an important role in generating many beneficial species, such as $OH•$, O_3, H_2O_2, NO_2^-, and NO_3^- [18], [33], [46]–[49]. This humidity could be in both forms of water vapor in the air and water absorbed in soil grain (soil humidity). Therefore, in this research, the soil had been sprayed with tap water before the plasma treatment process. It was expected that the chemical chain reaction could be enhanced in humid soil grain.

Regarding the results of plasma–treated soil characteristics, it could be confirmed that the plasma treatment has significantly affected the soil characteristics. The soil characteristics analysis has indicated the influence of air plasma treatment on soil quality. The pH of the plasma-treated soil could be improved from the slightly acidic soil becoming more neutral, which is suitable for plant growth. An increase in the soil pH after air plasma treatment would arise from the electrolysis of humidity (water) in the soil and ambient environment [50], [51]. During the treatment process, the water (from water vapor in the air and soil humidity) would be decomposed to O_2 and H_2 gas via an electrolysis process caused by plasma/water interactions [27]. The production of H_2 gas would result in a basicity increase. Therefore, the pH of air plasma-treated soil has been improved from slight acidity become neutral.

Total Kjeldahl Nitrogen (TKN) is the total concentration of nitrogen (or %Nitrogen) in both organic and inorganic (ammonia and ammonium (NH_3/NH_4^+) forms [41], [42]. Therefore, regarding the analysis of TKN in soils, it could be confirmed that the optimal air plasma treatment could enhance the percentage of nitrogen content in plasma-treated soil, which plays an essential role in plant growth as fertilizer. The most essential chemical species generated in air plasma for agricultural applications are the radicals of O•, OH•, NO•, and NO_2• [8]. These short-lived RONSs would chemically react with other gas or liquid atoms, and molecules, resulting in various beneficial by-product alternate sources of N-containing fertilizers such as NO_2^-, and NO_3^-. Moreover, O_3 and H_2O_2 would contribute to the microbial inactivation process [7], [12], [15]–[17], [26]–[28], [30]–[33], [52]. These species would diffuse into the plasma-treated soil during the treatment process, and react with the soil grains and their compounds [33], [46], [48], [49].

Regarding Fig. 8b), it could be noticed that TKN is increased when the soil has been treated with high supplied voltage and short treatment time. The TKN has seemed to be declined with the long-time treatment at the high supplied voltage (plasma treatment at 12 and 15 kV). Moreover, the results show that treatment at a too-high supplied voltage (plasma treatment at 15 kV) has been likely to suppress the production of TKN. This is in contrast to the case of treatment at the low supplied voltage and discharge current pulses (plasma treatment at 9 kV), whose TKN has increased with treatment time. The TKN at the first 15 min-treatment sorted from low to high has been 9, 15, and 12 kV, respectively. These results have been consistent with the intensity of the N_2 second positive system illustrated in Fig. 5. This could imply that the supplied voltage and the treatment time have influenced the TKN in plasma-treated soil. Besides the fact that the optimal supplied voltage affects the effective production of RONSs, a possible hypothesis of supplied voltage and treatment time dependence on the TKN of plasma-treated soil would be the joule heating caused by the high discharge current pulses (as shown in Fig. 4) flowed through the treated-soil during plasma-treatment. The heat accumulation in plasma-treated soil would cause N gaseous and moisture losses, and it would affect N-cycling transformation [5], [9].

According to the preliminary study, it could be confirmed that the RONSs generated during air plasma treatment by SPPG have a positive effect on the TKN of soil, and morning glory growth. However, air plasma could also contribute to soil enhancement in various other aspects, such as microbial inactivation, chemical residue decomposition, acid-base properties, electrical conductivity, and mineral fertilizer, as mentioned in the introduction part [7], [12], [31], [32], [34], [15]–[19], [26], [27], [30]. However, the soil is a rather complicated media, which contains many unknown compounds in various states (gas, liquid, and solid). Therefore, the in-detail chemical and physical mechanism of plasma-soil interaction, including the gaseous transport characteristics in the soil during soil treatment, still need to be more clarified.

5. Conclusion

A spark plug plasma generator has been proposed for agricultural soil enhancement. The impact of air plasma generated by the spark plug plasma generator on soil treatment has been investigated. The targeted soils have been plasma-treated at different treatment times (0, 15, and 30 min) and different AC-supplied voltages (9, 12, and 15 kV). The application of plasma-treated soils for morning glory planting has shown positive results. The germination rate, the length, and the fresh weight of morning glory planted in the plasma-treated soil could be significantly enhanced in almost all cases. The pH of all the plasma-treated soils could be improved from slightly acidic soil to more neutral. At this time, the optimal experimental condition has been found in the plasma treatment at 12 kV for 15 min, which could enhance the pH and the TKN up to 1.17, and 4.33 times higher than the ones of the control group, respectively. From the experimental results, it could be confirmed that the proposed air plasma generated by the spark plug plasma generator could enrich the plasma-treated soil significantly, and it could be another promising technique for soil improvement. However, the treatment time and the supplied voltage need to be optimized.

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