Improvements in plant growth rate using underwater discharge

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Abstract. The drainage water from plant pots was irradiated by plasma and then recycled to irrigate plants for improving the growth rate by supplying nutrients to plants and inactivating the bacteria in the bed-soil. Brassica rapa var. perviridis (Chinese cabbage; Brassica campestris) plants were cultivated in pots filled with artificial soil, which included the use of chicken droppings as a fertiliser. The water was recycled once per day from a drainage water pool and added to the bed-soil in the pots. A magnetic compression type pulsed power generator was used to produce underwater discharge with repetition rate of 250 pps. The plasma irradiation times were set as 10 and 20 minutes per day over 28 days of cultivation. The experimental results showed that the growth rate increased significantly with plasma irradiation into the drainage water. The growth rate increased with the plasma irradiation time. The nitrogen concentration of the leaves increased as a result of plasma irradiation based on chlorophyll content analysis. The bacteria in the drainage water were inactivated by the plasma irradiation.

1. Introduction
Hydroponics is widely used in the cultivation of many kinds of vegetable and fruit. In hydroponics, artificial nutrient solutions are used as fertiliser, circulated in the cultivation bed to improve the growth rate of the vegetables and fruits. The nutrient solutions used for plant growth in greenhouses are rich in electrolytes, such as K+, NH4+, Ca2+, Mg2+, NO3-, H2PO4-, and SO42- [1]. Owing to this, the drainage nutrient solutions employed in greenhouses have relatively high nutrient ion concentrations, and therefore, they can be reused to save fertilisers and to prevent contamination of water sources with undesired ions, such as nitrate and dihydrogen phosphate [2].

One of the major problems encountered when recycling drainage solutions in soilless and/or artificial soil-based cultures is an exponential increase in pathogenic bacteria concentrations, such as agrobacterium, powdery mildew, and Fusarium wilt, among others [3, 4]. Furthermore, an excess
accumulation of Na⁺, Cl⁻ and other nutrient ions in irrigation water is also a major problem [5]. In such cases, to reduce the incidence of pathogenic fungi and bacteria in the root environment, the pathogenic fungi and bacteria must be inactivated in the drainage solution. Additionally, to reduce the accumulated Na⁺ and Cl⁻ concentrations, the initial ion concentrations in the artificial fertiliser must be decreased.

Discharge underwater is a promising candidate for solving such problems because discharge produces chemically active species, such as atomic oxygen (O), ozone (O₃) and hydroxyl radicals (OH), which work to inactivate the pathogenic fungi and bacteria [6-11]. Additionally, underwater discharge produces nitric acid, which works as a fertiliser [1, 6]. This paper describes the effect of underwater discharge on both the growth rates of plants and the associated bacterial activities.

2. Materials and methods

2.1. Materials

Figure 1 shows schematics of the setup used for plant cultivation. The bed-pot was placed on a stand with a height of 10 cm. *Brassica rapa var. perviridis* (Chinese cabbage; *Brassica campestris*; Atariya Noen Co. LTD) was used as the specimen, cultivated in the bed-pots filled with artificial soil. The artificial soil was composed of expanded vermiculite (Gleen Plan Co. LTD) and Loamy soil (Gleen Plan Co. LTD) mixed at a rate of 1:2. Chicken droppings (1 g in weight) were placed on the soil surface as a fertiliser. The bed-pot was 9 cm in upper diameter, 7 cm in lower diameter and 7 cm in height. The bed-pot was filled with 93 g of artificial soil. Distilled water was supplied to the bed-soil on the first day of cultivation. A portion of the water was absorbed by the plants and the bed-soil, and the remainder was flown through a hole located at the centre of the lower side of the bed-pot. The drainage water was collected in a tank located under the bed-pot and then was recycled as the bed-soil water supply. The seedlings of *Brassica rapa var. perviridis* were cultivated for three days at 25°C in a dark room after sowing. The three seedlings were planted in the bed-pot and then were cultivated for 28 days in a room near windows. The room temperature was approximately 20°C.

2.2. Plasma reactor

A schematic of the plasma reactor used to treat the drainage water is shown in figure 2. The reactor was 7 cm in width, 7 cm in length and 12 cm in height, i.e., a total of 250 ml in volume. Air was injected into the water at an air flow rate of 0.5 L/min using a glass tube placed on the lid. A tungsten wire measuring 0.2 mm in diameter was located in the glass tube, used as a high-voltage electrode to
generate the plasma within the drainage water. The drainage water was grounded by a SUS316 wire measuring 0.2 mm in diameter. The drainage water from the bed-pot emptied into the plasma reactor and then was treated by plasma irradiation, with the plasma produced in the glass tube and in the air bubble injected into the water through the glass tube. The plasma irradiation times were set as 10 and 20 minutes.

**Figure 3.** A diagram of the magnetic pulse power generator circuit.

The pulsed high voltage was supplied by a magnetic pulse compression circuit (Suematsu Electronics CO., LTD., MPC-3000S SP, Japan), as shown in figure 3, and was applied to the high-voltage wire electrode located in the glass tube. The capacitor $C_0$ was charged to the charging voltage by the charger. The energy stored in $C_0$ was transferred to $C_1$ through a pulse transformer, PT. The pulsed voltage was produced on the secondary side of the pulse transformer. The pulsed voltage was compressed by saturable inductors ($SI_1$, $SI_2$ and $SI_4$) and capacitors ($C_2$ and $C_3$). $SI_3$ was connected in parallel with $C_3$ to shorten the pulse width of the output voltage ($v_O$) [12].

Figure 4 shows typical waveforms of the output voltage ($v_O$) and the voltages on the capacitors $C_1$ ($v_{C1}$), $C_2$ ($v_{C2}$) and $C_3$ ($v_{C3}$) when the reactor was not connected to the circuit. The pulse compression procedure can be observed clearly. The pulse width of $v_{C1}$ is 1.19 $\mu$s and is compressed to a $v_O$ of 130 ns using magnetic compression processes. As can be seen in the figure, the output voltage has a peak value of 21 kV, and its rise time is 57 ns. The LC oscillation and the reflection due to the impedance mismatch cause the voltages to oscillate. The pulse repetition rate is maintained at 250 pps with a peak voltage of 30 kV in the experiment. The polarity of the applied voltage is fixed as positive. The energy in the reactor per pulse is calculated by integrating the electric power obtained by the output voltage and the current over time.

**Figure 4.** Typical output voltage waveforms of the magnetic pulse compression circuit without connection to the reactor.

**Figure 5.** Photographs of *Brassica rapa var. perviridis* cultivated for 28 days at (a) w/o plasma and with (b) 10 min. or (c) 20 min. of irradiation per day.
2.3. Analytical methods

The effect of plasma irradiation in the drainage water on the growth rate of Brassica rapa var. perviridis was evaluated by the amount of dried weight and the time history of the leaf length. The leaf lengths were monitored once per day during cultivation. The dried weight was obtained from cropped Brassica rapa var. perviridis after 28 days of cultivation. The cropped Brassica rapa var. perviridis was dried at 75°C for 48 hours using a constant-temperature box (Isuzu; Incubator SFR-113S). The weight was averaged from three samples from each pot. The number of bacteria in the drainage water was obtained by a colony counting method using a plate count agar. The bacteria were cultivated at 35°C for 48 hours. The nitrite and nitrate ions in the drainage water were measured with Ion Chromatography (IC) analysis. The nitrogen concentration of the leaves was measured as the chlorophyll content (Soil and Plant Analyser Development; SPAD) with a SPAD-502 meter.

3. Results

3.1. Growth rate

Figure 5 shows photographs of Brassica rapa var. perviridis at 28 days of cultivation for various plasma irradiation times. The plasma was produced in the drainage water using the plasma reactor mentioned in figure 4. The plasma was irradiated in the drainage water for 10 and 20 minutes each day. One group consisted of three cultivated pots of Brassica rapa var. perviridis. Another group (the control) was cultivated without plasma irradiation. All Brassica rapa var. perviridis plants grew by 28 days of cultivation. Figure 5 shows that the leaf size of the plants increased with plasma irradiation, changing with the irradiation time.

![Figure 6](image1.png)  
*Figure 6.* The dried weight of cropped Brassica rapa var. perviridis after 28 days of cultivation for various plasma irradiation times.

![Figure 7](image2.png)  
*Figure 7.* The time history in length of cultivated Brassica rapa var. perviridis leaf for various plasma irradiation times.

Figure 6 shows the dried weights of cropped Brassica rapa var. perviridis at 28 days after cultivation for various plasma irradiation times. The error bars show the standard deviations of the data. The dried weight of the plant without the plasma irradiation was an average weight of 0.011 g. The dried weight increased to 0.044 and 0.076 g as a result of 10 and 20 minutes of plasma irradiation, respectively. These values correspond to 3.9 and 6.6 times incremental increases in comparison to that of the control group. The statistical significance was confirmed by t-test with an accuracy of $P < 0.01$.

Figure 7 shows the time history in length of the cultivated Brassica rapa var. perviridis leaf for various plasma irradiation times. The leaf length in all cases was found to increase gradually with cultivation duration. The increase in the leaf length was saturated at 7 days after cultivation without plasma irradiation. The leaf length at 28 days of cultivation reached 38 mm without plasma irradiation. The leaf length at 28 days of cultivation increased to 80 and 95 mm as a result of 10 and 20 minutes of plasma irradiation, respectively. These values correspond to respective increases of 2.1 and 2.5 times in comparison to that of the control group.
3.2. Inactivation of bacteria

Figure 8 shows the time history of the bacteria count in the drainage water of cultivated *Brassica rapa var. perviridis* for various plasma irradiation times. The bacteria count was found to increase from 4.0 to 5.5 log-CFU at 28 days of cultivation without plasma irradiation. However, the bacteria count in the drainage water after 28 days of cultivation shows approximately the same value at day 0 of cultivation under the plasma irradiation condition. The bacteria count decreases by 2 log-CFU with the application of plasma irradiation into the drainage water. These results indicate that plasma irradiation of the drainage water is effective for inactivating bacteria not only in the drainage water but also in the bed-soil filled in the cultivation pots.

4. Discussion

The results of this study confirm that the growth rate of the plant *Brassica rapa var. perviridis* can be improved by plasma irradiation. The use of plasma in the water can supply many kinds of chemical species, such as OH, O, O₃, NO₂, NO₃, and H₂O₂, among others [11, 12]. Nitrate and nitrous species in the drainage water were measured to clarify the effect of plasma irradiation on the plant growth rate because nitrous nitrogen typically works as a fertiliser in plant cultivation.

![Figure 8](image-url)

**Figure 8.** The time history of bacterial count in the drainage water of *Brassica rapa var. perviridis* cultivation for various plasma irradiation times.

![Figure 9](image-url)

**Figure 9.** The concentration of nitrate nitrogen (NO₂⁻) and nitrous nitrogen (NO₃⁻) in the drainage water at 28 days of cultivation for various plasma irradiation times.

Figure 9 shows the concentrations of nitrate nitrogen (NO₂⁻) and nitrous nitrogen (NO₃⁻) in the drainage water at 28 days of cultivation for various plasma irradiation times. Nitrate and nitros nitrogen were not detected in the drainage without plasma irradiation treatment. Nitrate and nitrous nitrogen species were produced by plasma irradiation and increased with the irradiation time. The plasma causes the following reactions to occur in the air bubble [13]:

\[
\begin{align*}
N_2 + O_2 + e^- & \rightarrow 2NO + e^- \quad (R1), \\
2NO + O_2 & \rightarrow 2NO_2 \quad (R2), \\
H_2O + e^- & \rightarrow OH + H + e^- \quad (R3), \\
NO + OH & \rightarrow HNO_2 \quad (R4), \\
NO_2 + OH & \rightarrow HNO_3 \quad (R5). 
\end{align*}
\]

The drainage water was acidified with HNO₂ and HNO₃ as HNO₂(aq) and HNO₃(aq) because the Henry constants of HNO₂ and HNO₃ are larger than that of the other species produced with the air plasma [14].

Figure 10 shows the nitrogen concentrations of the leaves of *Brassica rapa var. perviridis* at 28 days of cultivation for the various plasma irradiation times. The nitrogen concentrations were...
evaluated with the SPAD (Soil and Plant Analyser Development) value using a chlorophyll meter. The nitrogen concentration in the leaf was found to increase with the application of plasma irradiation into the drainage water. Generally, plants absorb NO$_3^-$ (aq) as nutrients in the root, derived from the soil and the supplied water. NO$_3^-$ (aq) in the drainage water is recycled because the water supplied to the bed-pot is produced by plasma irradiation, as shown in Fig. 9. The experimental results shown in Fig. 10 indicate that the produced NO$_3^-$ (aq) ions are absorbed from the roots of *Brassica rapa var. perviridis* and are carried to the leaves.

![Figure 10. The nitrogen concentration of *Brassica rapa var. perviridis* leaves at 28 days of cultivation for various plasma irradiation times.](image)

![Figure 11. The time history in length of cultivated *Brassica rapa var. perviridis* leaves for various plasma irradiation times.](image)

The experimental results shown in Fig. 9 and 10 strongly suggest that the increase in plant growth rate as a result of plasma irradiation of the water supplied to the bed-soil for plant cultivation is mainly caused by the air plasma-produced NO$_3^-$ (aq) produced. To confirm the mechanism, the *Brassica rapa var. perviridis* was cultivated for 28 days under three different conditions, including 1) w/o plasma irradiation and w/o an additive (the control), 2) 30 minutes of plasma irradiation and w/o an additive, and 3) w/o plasma irradiation and with a HNO$_3$ addition as the additive but w/o plasma irradiation. The HNO$_3$ concentration in the drainage water was adjusted to 7 ppm, which was almost in agreement with that following 30 minutes of plasma irradiation. Figure 11 shows the time history in length of the cultivated *Brassica rapa var. perviridis* leaves under the three different conditions. The leaf length in all cases was found to increase gradually with cultivation duration. The increase in leaf length also was saturated at 7 days after cultivation without plasma irradiation or HNO$_3$ addition. The leaf growth rate was improved not only with plasma irradiation but also with HNO$_3$ addition. The growth rate at 7 ppm of HNO$_3$ addition was in good agreement with that at 30 minutes of plasma irradiation. This result clearly shows that NO$_3^-$ (aq) production with the plasma is a dominant factor for increasing the plant growth rate.

5. Conclusions
The plasma was generated using a magnetic pulse compression pulsed power generator to improve the plant growth rate in a bed-pot based cultivation system. The experimental results showed that the growth rate increased significantly by the application of plasma irradiation to the drainage water. The growth rate of the plants increased with the plasma irradiation time. The bacteria in the drainage water were inactivated following plasma irradiation. The nitrate and nitrous nitrogen species were produced by the application of plasma irradiation to the drainage water. The produced nitrous nitrogen ions were absorbed by the plants, becoming a dominant factor for improvements in the plant growth rate by the plasma irradiation.
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