Growth Acceleration Effects of Air Anions in Endive and Lettuce, and Economic Feasibility of Their Application

So-Ra Lee[1], Min-Jeong Song[2], and Myung-Min Oh[1*]

[1]*Division of Animal, Horticultural and Food Science, Chungbuk National University, Korea*

[2]*Brain Korea 21 Center for Bio-Resource Development, Chungbuk National University, Korea*

[2]*G+Flas Life Sciences, Inc., Seoul 08790, Korea*

***Corresponding author**: Tel: +82-43-2612530, E-mail: moh@cbnu.ac.kr

Abstract. Generally, anions are the molecules that have gained one or more extra electrons, and oxygen anions are the most commonly present anions in the atmosphere. Several studies have reported the improvement in plant respiration and growth on application of air anions to several plants. Nevertheless, there is still limited information on the relationship between air anions and plant growth. In this study, we confirmed the effect of air anions on the growth of lettuce and endive, explored their relationships, and further analyzed the economic feasibility of plant factories. Endives and two cultivars of lettuce were cultivated with the application of air anions. Endive plants applied to low concentration of air anion (1×10^4–5×10^4 ions·cm^{-3}) showed vigorous growth at 2 and 4 weeks of treatment. Low-level air anion improved growth characteristics such as leaf area and shoot fresh weight, although there was no significant difference in leaf shape index, leaf number, and chlorophyll content. Low levels of air anions led to 34% and 41% higher shoot growth than the control at 2 and 4 weeks of treatment, respectively. In addition, the photosynthetic rate of plants treated with the low-level air anion was 31% higher than that of the control at 3 weeks after treatment, which supported the results of shoot growth. Medium and high levels (7×10^5–12×10^5 ions·cm^{-3} and 15×10^5–20×10^5 ions·cm^{-3}) led to an increase in leaf area and shoot growth numerically at 4 weeks of treatment, but no significant difference between the control and treatments was observed. Lettuce plants treated with air anions (5×10^5 ions·cm^{-3}) showed vigorous growth after 28 days of treatment. Exposure to air anions improved growth characteristics, such as leaf area and shoot biomass, although there was no significant difference in leaf number and chlorophyll content. Profitability analysis in a plant factory currently in operation revealed that the annual net profit per 1,500 m^2 of cultivation area was about $ 8,000 and $ 7,000 for red leaf lettuce and lollo bionda lettuce, respectively. Therefore, the application of air anions to leafy vegetables in plant factories or greenhouses could increase crop production, resulting in high economic feasibility.

Keywords: Electric field, Photosynthesis, Mineral uptake, Crop productivity, Commercial viability, Energy use efficiency

1 Introduction

Electric potentials near the surface of the Earth are approximately 150–300 V/m on average fair-weather conditions, and plants growing on the Earth are exposed to these natural electric fields (Ellis and Turner, 1978). In the atmosphere above the Earth, air molecules above the altitude of 50 km are ionized by solar energy and this region is called the ionosphere. The 70–140 km of the ionosphere has high conductivity and a small potential within it, so it acts as a perfect magnetic shield in the atmosphere. In the region lower than the shield, the atmosphere acts as a dielectric, creating a positive potential between the Earth and the ionosphere, also called the electrosphere. The number and types of charged particles in the atmosphere depend on weather, season, climate, region, and other factors (Chalmers, 1967). These differences affect the electrical condition of the atmosphere, resulting in a positive potential near the surface of the Earth on sunny days, which reverses and becomes stronger on rainy days. In addition, greater the environmental pollution, larger the potential, whereas in an area with less environmental pollution, such as the sea, the potential is relatively low.

While the physiological effects of environmental factors such as light, temperature, and humidity on plant growth have been studied for a long time and the related literature is also quite extensive, studies on effect of the electric fields on plants are still not organized (Murr, 1963). However, as it has become increasingly clear that the electrical environment can affect plant growth, whether positively or negatively, it is necessary to study the response of plants to electric fields in addition to other environmental factors.

Since plant cells repeatedly excrete and absorb ions through the membrane, charged ions exist in the cytosol, generating an electric field inside the plants (Blinks, 1949; Burr and Northrop, 1939). In general, plants exposed to an electric field between the Earth and the atmosphere have a small electric current. When exposed to an electric field of sufficiently high potential, such as a thunderstorm, a point discharge occurs, resulting in a relatively high current flow (Schonland, 1928; Chalmers and Ette, 1966). The effect of electric current on plant growth is not yet completely understood, but experiments have been conducted in some natural and virtual environments. An artificially applied electric field can promote plant growth, as confirmed by studies since the early 20th century (Blackman, 1924; Cholodny and Sankewitsch, 1937; Ellis and Turner, 1978; Jorgensen and Stiles, 1918; Lemstrom, 1904; Murr, 1963; 1964; 1965a; 1965b). Since then, 'electro-culture', a technology that utilizes electricity for plant cultivation, has been employed mainly in greenhouses where environmental control is possible (Pohl and Todd, 1981; Yamaguchi and Krueger, 1983). According to a previous study, a strong electrostatic field induces the rotation movements and translation of electric charges and dipoles, and can also change the chemical reaction rate, molecular binding force, and shape and structure of protein molecules (Cramariuc et al., 2005).

We applied this electric cultivation method to two extensively used vegetables, endive (*Cichorium endavia* var. *crispum*) and lettuce (*Lactuca sativa*), to confirm the growth-promoting effect and further analyze whether it could be used commercially. The results of this analysis are discussed in the article.

2 Materials and Methods

2.1 Plant materials and culture conditions

Endive (*C. endavia* var. *crispum* cv. Green curled ruffec) seeds were germinated on rock wool cubes (40×40×40 mm) (KP40, UR Media, Seoul, Korea). Seedlings were allowed to grow for 18 days and transplanted into a nutrient film technique (NFT) system in a walk-in chamber equipped with LEDs (red: blue = 8:2, 180 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux densit (PPFD), 12 h on). The chamber was divided into four separate sections, and the average air temperature and relative humidity in each section were maintained at 20 ^{o}C and 60%, respectively. A half-strength formula of the Hoagland nutrient solution was supplied to the NFT system (Hoagland and Aron, 1950). The electrical conductivity (EC) of the nutrient solution was maintained at 1.15 $dS \cdot m^{-1}$ and pH was adjusted to 6.0. The carbon dioxide (CO_2) concentration in the chamber was measured using a sensor (MV250, Soha-Tech, Seoul, Korea) and maintained at 1000 ppm using a CO_2 controller (VT200CNS, Soha-Tech, Seoul, Korea).

In order to establish an approach using air anions, we conducted a further experiment to verify the effectiveness of air anions in a 15 m^2 area of cultivation space in an actual commercially operated plant factory, InsungTec Co., Ltd, Yongin, Korea. Two cultivars of lettuce (*L. sativa*; lollo bionda cv. Multibaby and red leaf cv. Jeokchima) seedlings grown for 14 days were transplanted to NFT systems in the plant factory equipped with fluorescent lamps (100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD, 16 h on). The average air temperature and relative humidity in the plant factory during cultivation were maintained at 22 ^{o}C and 70%, respectively. The EC and pH values of the nutrient solution (N:P:K = 17.3:4.0:8.0) were measured every 2 days and adjusted to 1.3 dS $\cdot m^{-1}$ and 6.0, respectively. The positions of both plants were systematically rotated every other day to minimize growth differences caused by the imbalance of light and air anion distribution.

2.2 Application of air anion

Three levels of air anions (low, 1×10^4–5×10^4; medium, 7×10^5–12×10^5; and high, 15×10^5–20×10^5 ions$\cdot cm^{-3}$) were applied to obtain high-voltage air anion generators (TFB-Y49, Trumpxp, China) for 4 weeks after transplanting. The concentration of air anions was regulated by varying the distance between the plants and air anion generators (Fig. 1) and measured with an air anion counter (COM-3600, Com System, Tokyo, Japan). Lettuce plants were supplied with air anions at approximately 5×10^5 ions$\cdot cm^{-3}$ using the generators for 4 weeks. Plants receiving each concentration of treatment, as well as control, were placed in separate sections of the chamber, and the generators operated continuously throughout the day for the treatment period.

2.3 Plant growth

For every week of transplantion, five endive plants were collected per treatment. Fifteen lettuce plants per treatment were collected every two weeks of treatment. The plants were separated into aerial parts and roots and weighed using an electronic scale (Si-234, Denver Instrument, Bohemia, New York, USA). Both plant parts were oven-dried at 70 °C for 72 h to determine the dry weight. Leaf area was determined using a leaf area meter (LI-3100, Li-Cor, Lincoln, NE, USA), and leaf width and length were measured using a digital Vernier caliper (NA530-300S, Bluetec, Changwon, Korea). The leaf shape index (LSI) was calculated using the following equation: LSI = leaf length/leaf width (using the fifth leaf from the base). The chlorophyll content of lettuce leaves was measured using a portable chlorophyll meter (SPAD-502; Minolta, Osaka, Japan).

2.4 Photosynthetic rate

The photosynthetic rate of the endive plants was measured at 13, 18, and 21 d of air anion treatment. The photosynthesis of the fifth leaf from the base of each plant, a completely unfolded leaf, was evaluated using a portable photosynthesis analyzer (Li-6400, Li-Cor). The leaf chamber parameters were set as follows: flow rate, 400 μmol·s^{-1}; CO_2 concentration, 1000 μmol·mol^{-1}; PPFD, 180 μmol·m^{-2}·s^{-1}; temperature, 20 °C, which were similar to the growth conditions. Taking the diurnal fluctuation of the gas exchange rate into consideration, the rate was measured 2 h after the light was turned on.

2.5 Economic efficiency evaluation

Based on the results of lettuce plants, the economic efficiency of applying air anions in plant factories was evaluated by cost-benefit analysis. The energy consumption of the air anion generators was measured using a multimeter (FLUKE-115, Fluke, Everett, WA, USA) during the experiment. The total electric power consumed to control the growth conditions was equal between the control and treatment groups, and the only difference was the use of air anion generators. The price of lettuce used for the evaluation was based on the retail price provided by the Korea Agricultural Marketing Information Service (kamis.or.kr) at the time of the analysis.

2.6 Statistical analysis

The blocks used in each experiment were randomly designed. Data were analyzed by one-way analysis of variance (ANOVA) using the SAS program (Statistical Analysis System, 9.4 Version, SAS Institute Inc., Cary, NC, USA). The mean values were compared using Duncan's multiple range test and Student's t-test.

3 Results

3.1 Growth of endive and lettuce

Air anions induced remarkable differences in the growth of the endive and lettuce plants (Fig. 2). The shape of the endive leaves showed a tendency to be wider as the concentration of air anions increased at 14 days of treatment; however, there was no difference between the control group and the treatment group at the final harvest, 28 days of treatment (Fig. 3A). On the 14th day, the leaf area was significantly increased in the low treatment group and was approximately 1.2 times larger than the control, but there was no difference on the 28th day (Fig. 3B). For shoot growth, the fresh weights significantly increased in the low and high treatment groups compared to the control (1.5 and 1.3 times, respectively), and the dry weights showed a significant increase in all treatment groups by 1.3–1.4 times than the control (Fig. 3C, D). The fresh weight of roots was also significantly increased at low and high concentrations of air anions compared to the control groups by 1.4 and 1.5 times, respectively (Fig. 4). There was no observable difference in the dry weight of roots, but the treatment groups showed better root growth than the control (about 1.2–1.4 times).

The leaf number of red leaf lettuce was not increased by air anion on the 28th day of treatment, the final harvest, whereas the leaf area was significantly increased by approximately 1.3 times compared to the control (Figs. 2B, 5A, B). The fresh weight of shoots was also about 1.5 times greater than that of the control, and the dry weight was significantly increased by approximately 1.2 times (Fig. 6A, B). Similarly, for the lollo bionda lettuce, only the leaf area was increased by 1.5 times compared to the control (Figs. 2B, 5C, D). Although the shoot fresh weight did not show a significant difference between the control and treatment groups at 14 days of treatment, fresh and dry weights were significantly increased in the anion-treated lollo bionda lettuce at the 28th day by approximately 1.5 and 1.1 times, respectively (Fig. 6C, D).

3.2 Photosynthesis and chlorophyll content

In order to investigate the effect of air anons on photosynthesis in endive plants, photosynthesis rates were measured at 13, 18, and 21 days of treatment. There was no significant difference in the photosynthetic rate between the control and treatments on the 13th and 21st days, but low and medium concentrations of air anions induced significantly higher photosynthetic rates than control and high-concentration treatment (Fig. 7A). The SPAD value indicating the chlorophyll content was significanly decreased only at the high treatment at 2 weeks of treament, but did not show a significant difference at the 4th week (Fig. 7B). There was no significant difference in chlorophyll content in the leaves of two cultivar lettuces (Fig. 7C,D).

3.3 Economic efficiency for applying air anion

Table 1 shows the results of the analysis of the cost and profit of applying the air anions (5×10^5 ions·cm^{-3}) to two cultivars of lettuce in a section (15 m^2) of the plant factory in operation. Each of the 513 red leaf and lollo biona lettuce plants were grown for 4 weeks in one cropping season in the area, and the profit and loss for one year were calculated. The cost of air anion generators (96 units) used in the 15 m^2 scale was $ 25 (KRW 28,128), and the electric cost for the operation of the generators was about $ 1.5 (80.74 kWh; 21.23 KRW/1 kWh). As a result, the total cost for air anion treatment in this experiment was computed to be $ 26 (₩ 29,842).

The total production of red leaf lettuce grown at 15 m^2 for 4 weeks in the control and air anion treatment sections was 14.5 kg and 21.3 kg, respectively; thus, production increased by about 6.8 kg due to the air anion treatment (Table 1). When the actual wholesale price of red leaf lettuce [$ 1.1 per 150 g] was applied to the increased production, the total profit from red leaf lettuce production due to the application of air anions was about $ 51 / 15 m^2. The cost of applying air anions to lollo bionda lettuce was the same as that of red leaf lettuce. The total production was 14.2 kg and 21.6 kg in the control and treatment groups, respectively, and the production was increased by about 7.4 kg as a result of the air anion treatment. Therefore, based on the wholesale price of green lettuce, the total profit from lollo bionda lettuce production was about $ 47 / 15 m^2.

After calculating the net profit by subtracting the cost for air anions from the total profit, the net profit resulting from the application of air anion treatment for 4 weeks in 15 m^2 for red leaf lettuce was about $ 25, and for lollo bionda lettuce was about $ 21. Based on these results, if the cultivation scale is expanded to 1,500 m^2 (165 m^2 × 4 tiers) and the plants are cultivated seven times a year, the net profit would be < $ 7,788 for red leaf lettuce and $ 6,558 for lollo bionda lettuce (Table 2).

4 Discussion

Exposure to air anions accelerated the growth of endive and lettuce, and a primary change was observed in the shoots rather than the roots (Figs. 2–6). There have been many studies on the effects induced by electricity in plants, and the growth-promoting effect has been reported as the most representative response (Dannehl, 2018). Electroculture is the practice of applying a strong electric field or a source of small air ions for growing plants (Wechsler, 2015). In the 1990s, researchers investigated the effects of positive and negative ions in the air on barley (*Hordeum vulgare*), oat (*Avena sativa*), and garden cress (*Lepidium sativum*). They found that applied ions promoted crop growth (Blackman et al., 1923; Krueger et al., 1962; Maw, 1967). In our previous studies, a growth-boosting effect was observed when air anions were applied to lettuce, kale, and spinach (An et al., 2021; Lee et al., 2015; Song et al., 2014), and the application of electric current directly to the rhizosphere in kale exhibited a similar effect (Lee and Oh, 2021). These studies supported our results of promoting the growth of endive and lettuce plants by air anions.

Air anion treatment has shown the potential to cause positive changes in root growth. The air anions significantly increased the root fresh weight of the endive by 1.3–1.6 times (Fig. 4). Previously, Smith and Fuller (1961) reported that an electric field formed by air cations promoted the biosynthesis of indole acetic acid (IAA) in *Microcoleus vaginatus*. Furthermore, a study on tobacco callus suggested the possibility that 1–2 μA direct current (DC) promoted polar transport of IAA (Goldsworthy and Rathore, 1985). In our previous studies, we also confirmed that the development of the root was markedly enhanced by air anions or electric fields in kale and spinach (An et al., 2021; Lee et al., 2015; Lee and Oh, 2021). Therefore, in the current study, it is possible that the application of air anions increased the level of auxin in the plants, which moved easily to the roots and promoted root formation (Friml, 2003). In addition, root development promotes water uptake by plants and can induce positive shoot growth.

Air anions had a positive effect on the photosynthetic capacity of unit chlorophyll without changing the chlorophyll content of the endive plants (Fig. 7). We demonstrated that air anions or electric fields promote the photosynthesis in lettuce, kale, and spinach in our previous studies (An et al., 2021; Lee et al., 2015; Lee and Oh, 2021; Song et al., 2014). Elkiey et al. (1985) found that exposure to air ions (cations 1×10^5 ions·cm^{-3}; anions 4×10^5 ions·cm^{-3}) improved photosynthesis, respiration, and transpiration. Respiration was also promoted in *Arum maculatum*, common wheat (*Triticum vulgare*), and broad bean (*Vicia faba*) when plants were exposed to an electrostatic field of 5–10 kV/m (Sidaway and Asprey, 1968). In other words, the electric fields generated by air anions promote representative metabolic reactions in plants, such as photosynthesis and respiration, thereby promoting the growth of shoots and roots.

The induction of electric field promoted the absorption of essential mineral elements in orchard grass (*Dactylis glomerata*) and sorghum (*Sorghum bicolor*) (Murr, 1964). Our previous studies also showed that the accumulation of macro-elements, including P, K, Ca, Mg, and S, and micro-elements including Fe, Mn, B, Zn, Cu, Ni, and Mo, increased, resulting in increased growth (Lee et al., 2015; Lee and Oh, 2021). In the electric field formed by air anions, cations can be electrically attracted toward the cells of the leaf surface, corresponding to the relative negative charge. The increased cations, including K^+, in guard cells cause the cells to expand and open the stomata, aiding in the maintenance of high stomatal conductivity (Hopkins, 1999; Tıraşoğlu et al., 2005). Increased stomatal conductivity enables gas exchange and water movement, and consequently, photosynthesis, respiration, and transpiration can also be promoted (Wong et al., 1979).

An economic analysis was conducted to confirm whether the cultivation method utilizing electricity could be used commercially, and the results were positive (Tables 1,2). We evaluated profitability by applying the results of this experiment to a plant factory of 1,500 m^2 scale, currently in operation. The results revealed that the net profit resulting from application of air anions for one year was approximately $ 8,000 (equivalent to approximately 9 million KRW) for red leaf lettuce and $7,000 (approximately 7 million KRW) for lollo bionda lettuce, respectively. The method was applied to only a part of the space of the plant factory; if applied to the actual cultivation area of plant factory, much more net profit could have been obtained.

The increasing trend of yield differed depending on the plant species. When the plants were cultivated for one cropping season (4 weeks) using 96 air anion generators in a 15 m^2 of the plant factory, the net increased production was 6.8 kg for red leaf lettuce and 7.4 kg for lollo bionda lettuce (Table 1). Based on the results of this experiment, the economic effect of air anion treatment was found to be greater for red leaves than for lollo bionda lettuce. Therefore, it is suggested that a species associated with high growth on application of air anions, a high market price, and a short cultivation period should be selected. In conclusion, the treatment of leafy vegetables with air anions has a positive effect on its growth and is economically effective.

5 Conclusion

There has been a debate about the effect of electricity on plants for a long time. However, various research studies over the last decade have proved that the electric field can practically be applicable as a new cultivation technology to increase crop production. This current study suggests that electric fields should be considered as an important environmental factor affecting plant growth. Applying air anions or electric fields to crop cultivation could be a simple and economical method to improve plant growth. In addition, the time required for the crop to reach the saleable stage can be shortened, resulting in higher profits. However, because the type and intensity of applied electricity are diverse and they difference according to plant species, finding an appropriate application method is an essential step for the utilization of electric fields in crop cultivation. Further studies should elucidate the molecular mechanism by which electricity affects plant growth, leading to consistent plant response to electricity.

CRediT authorship contribution statement

Sora Lee: conceptualization, investigation, formal analysis, visualization, writing – original draft preparation. **Min-Jeong Song:** investigation, formal analysis. **Myung-Min Oh:** conceptualization, resource, writing – review and editing, project administration, funding acquisition

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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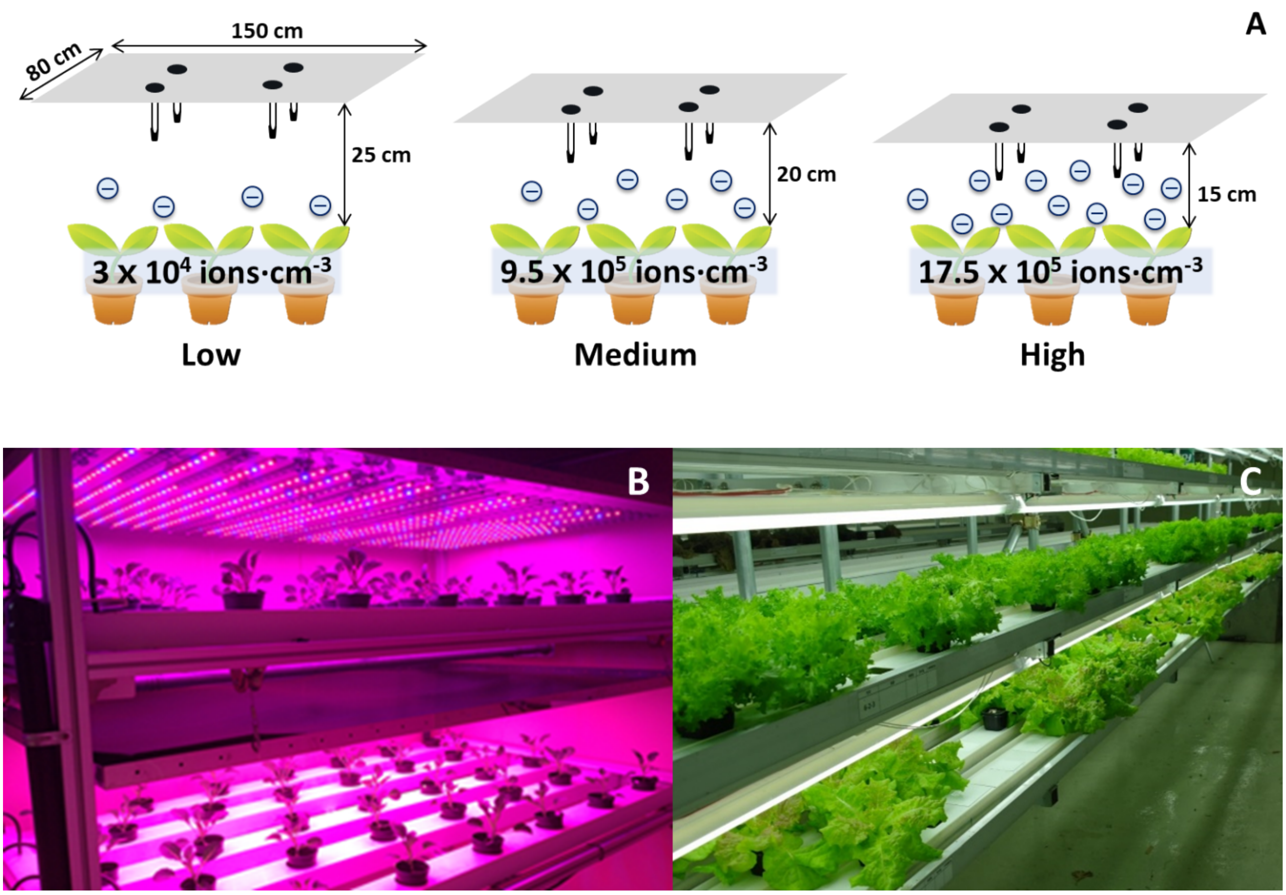


Fig.1. Distribution of air anions for each distance between plants (A), and air anion application in the endive (B) and lettuce experiment (C).

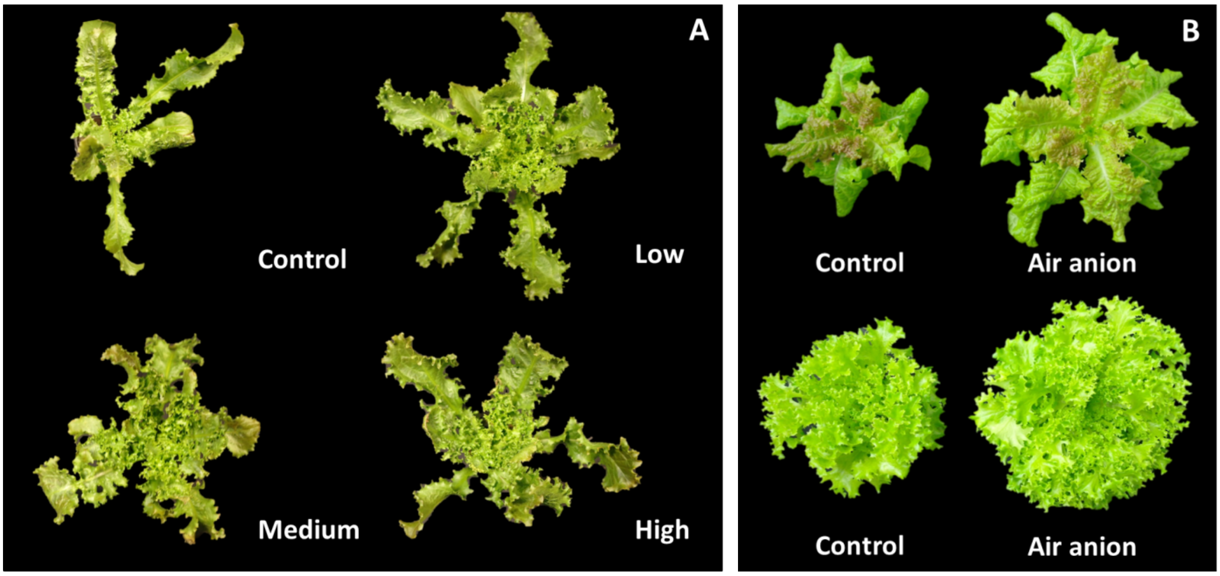


Fig. 2. Endive (a) and lettuce (b) plants grown under the application of air anions for 28 days.

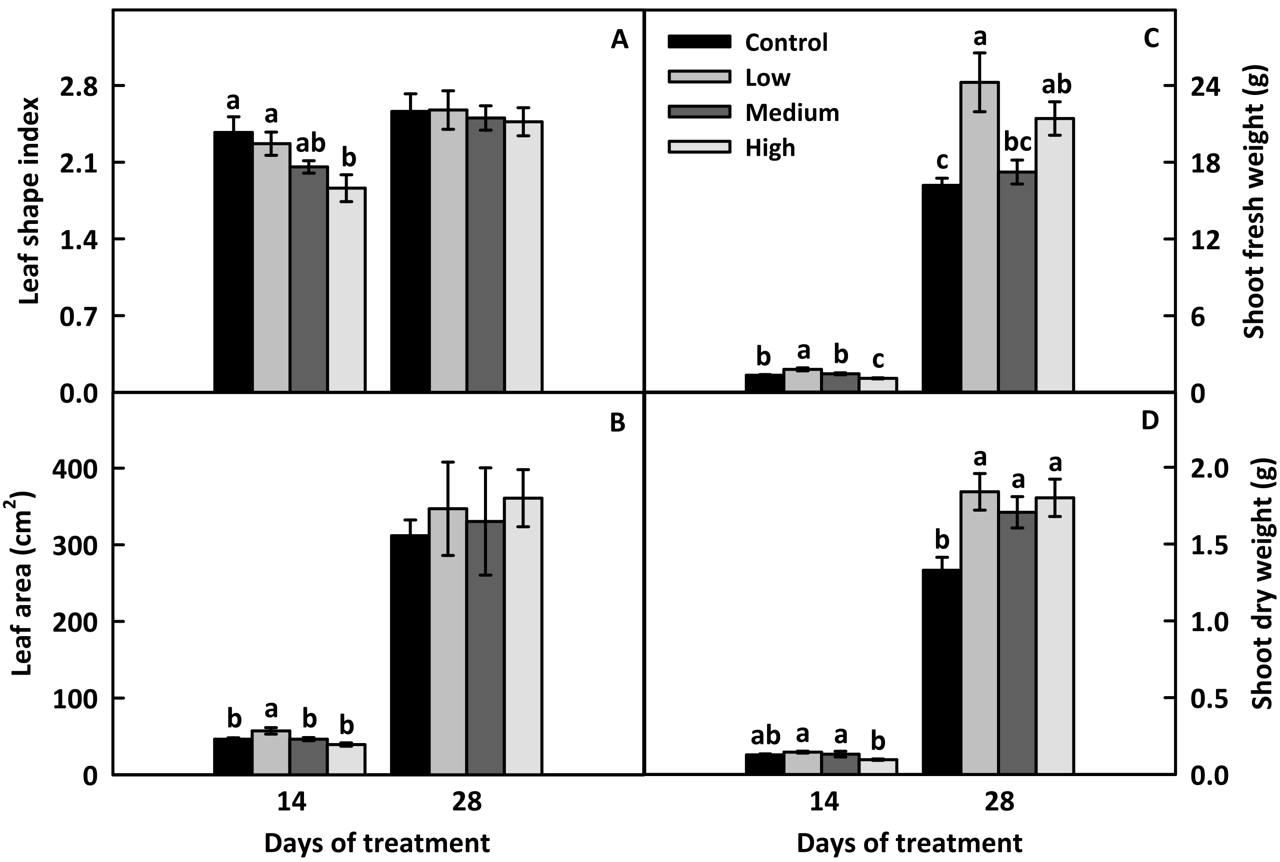
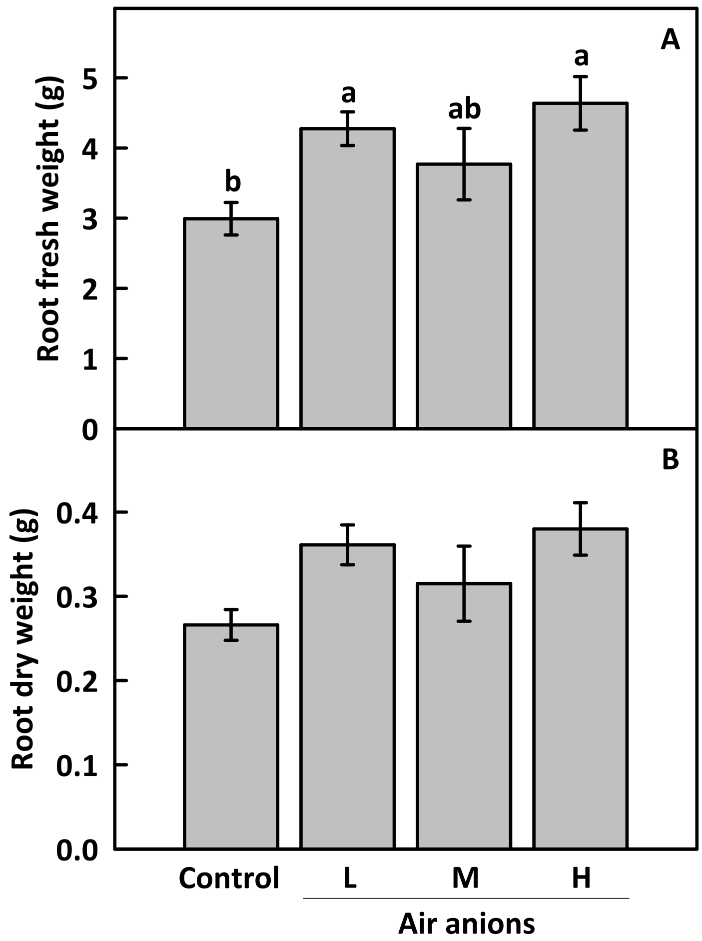


Fig. 3. Leaf shape (A), leaf area (B), shoot fresh (C), and dry weights (D) of endive grown under application of air anions for 14 and 28 days. Significant at p<0.01 (n=5).



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356 Fig. 4. Root fresh (A) and dry weights (B) of endive grown under application of air anions for 28 days.

357 Significant at $p<0.01$ (n=5).

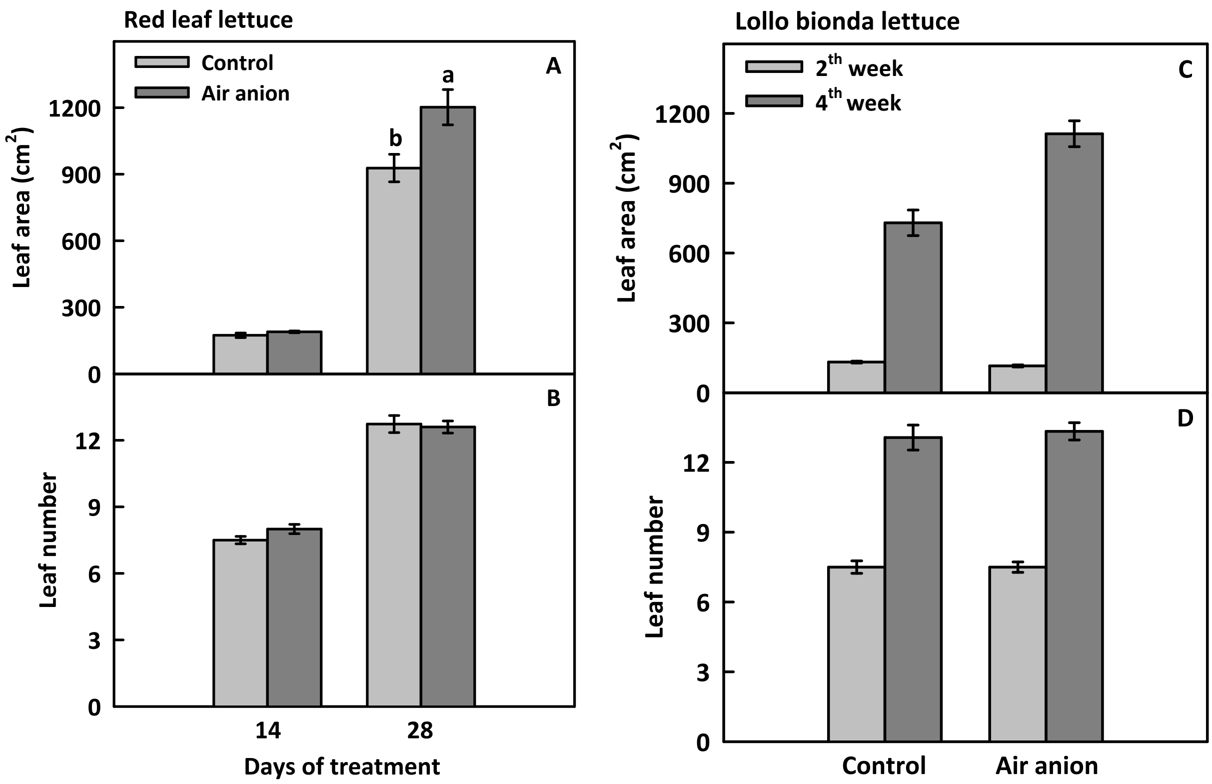

Fig. 5. Leaf area (A and C) and number (B and D) of two types of lettuce grown under application of air anions (5×10^5 ions·cm^{-3}) for 14 and 28 days (n=15). Significant at $p<0.001$ (n=15).

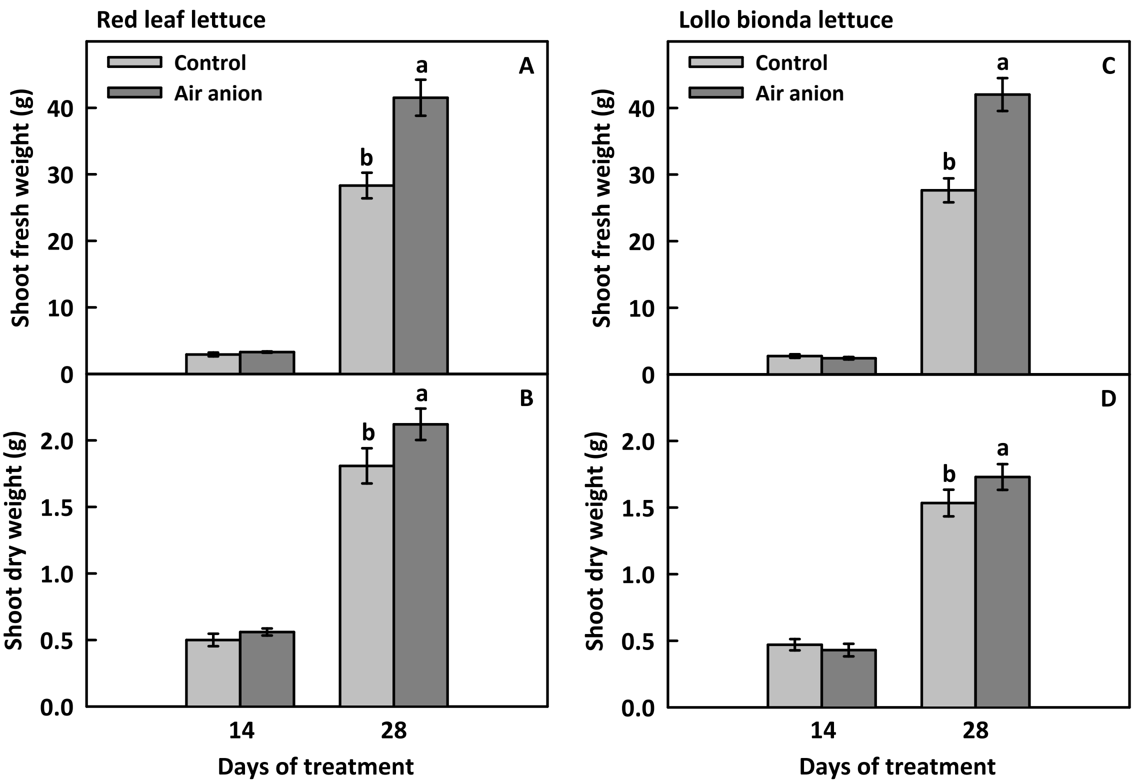

Fig. 6. Shoot fresh (A and C) and dry weights (B and D) of two types of lettuce grown under application of air anions (5×10^5 ions·cm^{-3}) for 14 and 28 days. Significant at $p<0.001$ (n=15).

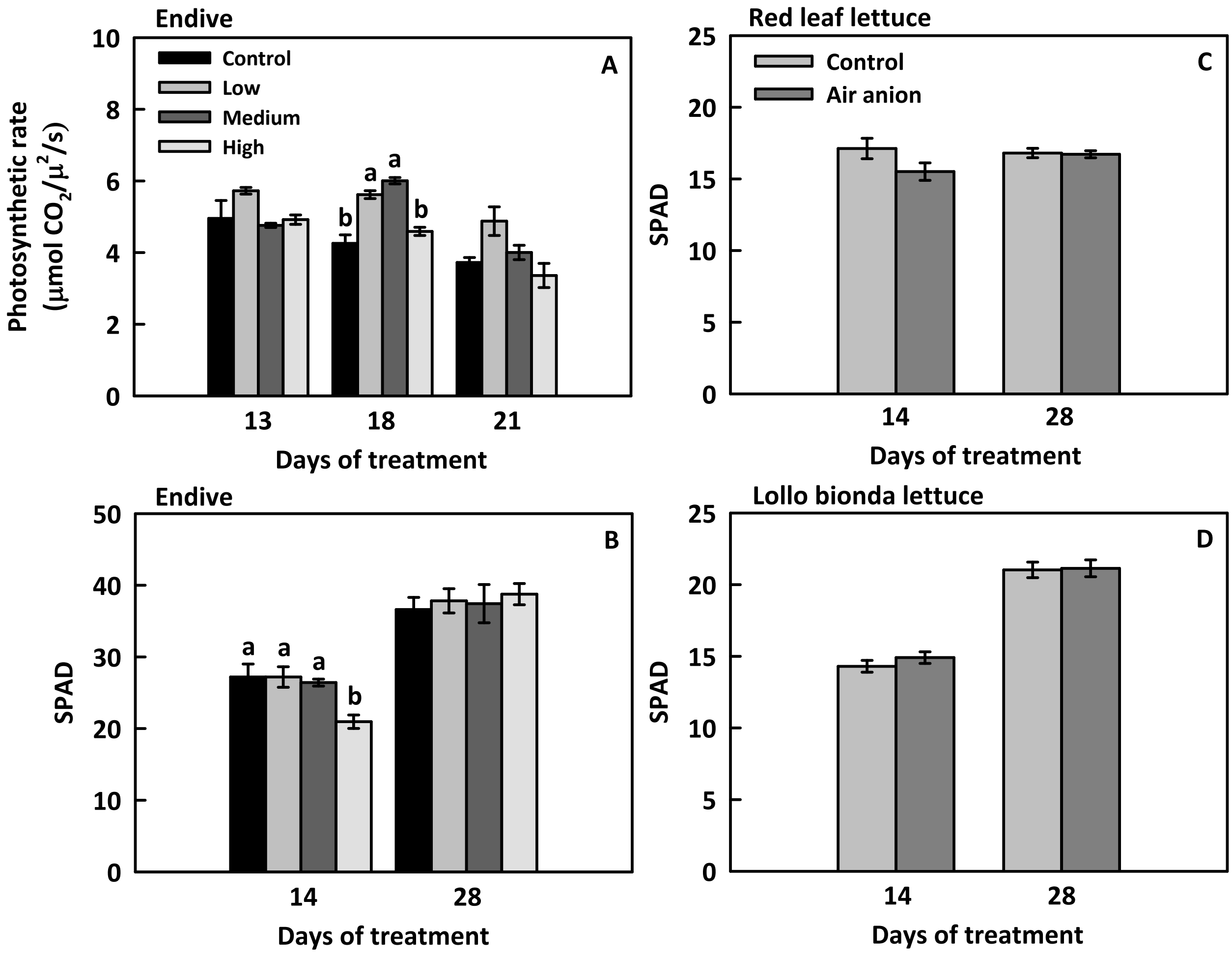

Fig. 7. Photosynthetic rate of endive grown under application of air anions at the day before harvest (13, 18, and 21^{st} day) (A). Chlorophyll content in endive (B) and lettuce leaves (C and D) after the application of air anions for 14 and 28 days of treatment. Significant at *p*<0.001 (n=5 for endive and n=10 for lettuce).

Table 1. Cost, yield, and benefit for applying air anions to two cultivars of lettuce cultivation in a plant factory

Type of lettuce	**Treatment**	
	Control	**Air anion**
Red leaf		
Cost ($)	-	26 (₩ 29,842)
Yield (kg)	14.5	21.3
Benefit ($)	-	51 (₩58,687)
Lollo bionda		
Cost ($)	-	26 (₩ 29,842)
Yield (kg)	14.2	21.6
Benefit ($)	-	47 (₩ 54,123)

Cultivation period: 4 weeks (1 harvest)
Cultivation area: 15 m^2
Lettuce price: $ 1.14 and 0.96 per 150 g for red leaf and lollo bionda lettuce, respectively
The exchange rate applied as of July 15, 2021 (₩ 1,140 / $ 1)
A set of air anion generators installed per unit area (15 m^2)
Considered the cost of the generators and consumed electricity

Table 2.4. Economic efficiency for applying air anions to two cultivars of lettuce cultivation in a plant factory

Type of lettuce	Net profit for unit area (15 m^2) (A)	Net profit for 1,500 m^2 (A × 100)
Red leaf	$ 177 (₩ 201,915)	$ 17,711 (₩ 20,191,500)
Lollo bionda	$ 149 (₩ 169,967)	$ 14,909 (₩ 16,996,700)

Cultivation period: 1 year (7 harvest)
Cultivation area: 15 m^2 × 4 tiers × 25 lines = 1,500 m^2
Lettuce price: $ 1.14 and 0.96 per 150 g, respectively
The exchange rate applied as of July 15, 2021 (₩ 1,140 / $ 1)
A set of air anion generators installed per unit area (15 m^2)
Considered the cost of the generators and consumed electricity