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Research Article

A New Technique to Realize a Drastic Acceleration of Crop Growth in the DFT Hydroponic Cultivation with Hyper-oxygenated Nutrient Solution

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ABSTRACT

Aeration of the nutrient solution has been tried in order to enhance the growth of leaf vegetables such as lettuce, rape, spinach etc, in the hydroponic cultivation with the DFT hydroponic cultivation system in greenhouses. In this study, we chose mini-bok choy as a test crop, and examined the daily changes of oxygen intake by the root in the hyper-oxygenated nutrient solution of the DFT hydroponic cultivation system, and revealed the presence of an unknown capacity of the root for oxygen intake from the nutrient solution, responding to the changes of light intensity, as it can take in oxygen from the hyper-oxygenated nutrient solution as an alternative oxygen source, but the oxygen intake does not run in the light conditions enough for photosynthesis. Mini-bok choy cultivated with the hyper-oxygenated nutrient solution with DO between 8.85 and 22.06 $mgO_2\ L^{-1}$ exhibited approximately 2.0 and 1.7 holds of the growth acceleration of its aerial part and root in the period of the experiment over 23 days. We presented a micro-bubble technique to create a hyper-oxygenated nutrient solution for realizing the dramatic acceleration of the crop growth with a minimum cost applicable to the actual hydroponic cultivation of the crop in a greenhouse.

Keywords: Hydroponics; Hyper-oxygenation; Micro-bubble; Mini-bok choy; Oxygen intake

INTRODUCTION

Greenhouse cultivation of horticultural crops has recently evolved as one of the most advanced styles of agriculture [1]. In this facility, the environmental conditions that affect the growth of the crop are well controlled, being monitored at all times. The adjustment of the concentration of carbon dioxide gas in the air has been treated as one of the primary issues to sustain or enhance the photosynthetic activity of the crop [2,3]. Frequent ventilation of the air or addition of carbon dioxide gas is often required to create enriched conditions of carbon dioxide gas of the air [2-6]. This technique focuses on the biosynthetic activity of the crop during the daytime, when the crop can self-produce oxygen gas by photosynthesis, using it partly for keeping its metabolic activity. However, the plant cannot undergo photosynthesis during the nighttime. Although the shoot is exposed to the air, the root aeration is limited and partly relies on the oxygen transmission from the shoot [7].

The diurnal fluctuation of oxygen transmission from the shoot to the root may bring oxygen stress to the root during the nighttime [7]. In particular, in the case of hydroponic cultivation of the crop, the root is always submerged in water, where oxygen is much less diffusible and soluble than in the air [8], and subject to oxygen stress throughout the nighttime. The endodermis of the root is known as an organ that has an ability to actively transport ions in one direction, resisting their diffusion back into the cortex [9]. Since this function requires energy, its activity is depressed under oxygen-stressed conditions that lead the crop to a restriction of glycolysis and respiration which decreases the adenylate energy status, a widespread decrease in biosynthetic activity, and a switch to pathways that consume less ATP [10,11]. Therefore, the shortage of oxygen supply to the root restricts the nutrient intake and various biosynthetic activities until the oxygen transmission

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from the shoot to the root resumes the next morning.

Recently, new types of water aerators such as the oxygen enricher [12] and micro/nano-bubble generator [13-16] have been developed. They release tiny air bubbles of less than 100 μm of the diameter, and these bubbles have a drastically larger capacity for dissolving oxygen gas compared to the water to the macro-bubbles released from conventional aquarium aeration devices [13,16]. In the research of horticulture, the new aeration devices have been applied to Deep Flow Technique (DFT) hydroponic cultivation of vegetables [12,17-19], aiming at creating dissolved oxygen (DO) saturated conditions or hyper-oxygenated conditions over 20 to 30 $mgO_2\ L^{-1}$ in the nutrient solution efficiently, enhancing their growth by the increase of oxygen transmission from the treated nutrient solution to the root of the cultivated crop. A small scale of the laboratory experiment with a DFT hydroponic cultivation system demonstrated that the fresh leaf weight of lettuce (*Lactuca sativa* L.) increased to 2.3 times heavier with hyper-oxygenated nutrient solution containing DO over 20 $mgO_2\ L^{-1}$ to the control with untreated one 14 days later [12]. The fresh leaf weight of rape (*Brassica campestris*) increased about 1.3 times heavier to that of the control 28 days later, creating max. 1.2 $mgO_2\ L^{-1}$ of higher DO conditions in the nutrient solution [17], and the aerial part of spinach (Spinacia oleracea L.) also grew to about 1.4 times heavier in fresh weight to that of the control 21 days later, creating a max. 1.0 $mgO_2\ L^{-1}$ of higher DO conditions in the nutrient solution [18] by the aeration of the nutrient solution with air micro-bubbles in the DFT hydroponic cultivation experiment. Although the detailed mechanisms of how the growth of the vegetables was promoted significantly are still not clear, these studies give us an empirical idea as aeration of the nutrient solution can awake the metabolic activity of the crops during the nighttime in the same way as the daytime, bringing a big promotion of their growth.

One of the authors of this paper, Hiroaki Tsutsumi, has developed a micro-bubble generator, eco-Bubble®, in collaboration with Takohgiken Co., Ltd. (Kumamoto, Japan) [15] to apply this new aeration device to aquaculture and plant cultivation in the fields, aiming at increasing DO supply drastically to the cultured aquatic animals [14,15] and plants when phytoplankton in the water and cultivated plants themselves cannot undergo photosynthesis during the nighttime. In this study, we chose mini-bok choy (*Brassica rapa* var. *chinensis*) as a test crop for the hydroponic cultivation experiment with the DFT hydroponic cultivation system, and conducted an experiment with a hyper-oxygenated nutrient solution created by releasing pure oxygen micro-bubbles in the pool actually used for the horticultural cultivation of vegetables by an agricultural corporation. We monitored the DO fluctuations of the nutrient solution of the hydroponic cultivation system and examined the impact of the elevation of DO of the nutrient solution on the respiratory activity from the roots of the mini-bok choy and its growth. We report what benefits the use of the hyper-oxygenated nutrient solution can bring to the DFT hydroponic cultivation of the crop with the results of the cultivation experiment, and discuss the mechanisms of the physiological responses of the crop to the hyper-oxygenated nutrient solution, including how the micro-bubble technique for creating the hyper-oxygenated nutrient solution can be applied to the acceleration of growth of the crop with a reasonable cost for practical horticultural cultivation.

MATERIALS AND METHODS

The cultivation experiment of mini-bok choy was conducted with the DFT hydroponic cultivation system for leaf vegetables in a green house, which is owned by an agricultural corporation, Kinugasa Co., Ltd. (located in Kikuyo-machi, Kikuchi gun, Kumamoto Prefecture, Japan). We prepared two pools for the cultivation experiment of mini-bok choy. Its seedlings were planted in sponges, which were fixed in every other hole of 120 in a Styrofoam planting panel (80 x 55 cm). 32 sets of this panel were prepared for the experiment, and 16 panels were put on the nutrient solution with a depth of 15 cm in each of the two pools (640 x 130 x 20 cm). The nutrient solution was gently circulated with a circulation pump.

The concentrations of the nutrients of the water in these two pools were adjusted to around 0.7 $mS\ cm^{-1}$ in electric conductivity throughout the period of the experiment, using a powder nutrient which contained mixed Rocket Power No. 2 and No. 3 manufactured by Nittofc Co., Ltd., Japan, at the weight ratio of 2:3. At one of these two pools, which is referred to as “Experiment”, two sets of the micro-bubble generator (eco-Bubble®-S1 (Input of power 395W in 60Hz), Taikohgiken Co., Ltd., Kumamoto, Japan) were installed at the brim of the middle part of the pool facing each other (Figure 1). The air intake of the nozzle of each micro-bubble generator was connected to the discharge port of a gas cylinder with 7 m^3 of pure oxygen gas (99.99%) with a plastic tube. The oxygen gas released as micro-bubbles with the mean diameter of about 15 μm from the micro-bubble generators will dissolve in about 1.25 m^3 of the nutrient solution in the pool with a dramatically higher efficiency than that of milli-sizes of bubbles released from the conventional air-stone (diameter 50 mm) [14,15]. Another pool with no aeration system is referred to as “Control”.

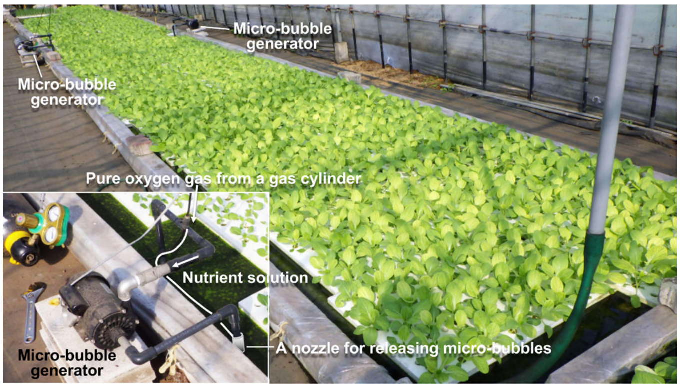

Figure 1: The DFT hydroponic cultivation system for mini-bok choy with two sets of micro-bubble generators for releasing pure oxygen micro-bubbles in the nutrient solution stored at a pool (640 x 130 x 20 cm) in Experiment.

The cultivation experiment of mini-bok choy was carried out at the two pools used for the DFT hydroponic cultivation system in the greenhouse. The experiment was conducted for 23 days between 8 November and 30 November in 2018. The temperature and DO of the nutrient solution were measured in the afternoon (13:00 to 15:00) in both Experiment and Control between November 13 and 30, using a multi-probe (ProODO, YSI/Nanotech Inc., U.S.). The temperature of the nutrient solution in Experiment, which had decreased from 18.6 °C to 13.9 °C, was slightly lower than that in Control (17.6 °C and 13.5 °C) during the period of the experiment. As for Experiment, each of the micro-bubble generators was run, and released 0.7 L of pure oxygen micro-bubbles per minute for four hours between 23:30 and 3:30 every day to dissolve oxygen gas to the nutrient solution. The changes of DO of the nutrient solution in both of Experiment and Control were monitored with a probe every 30 min. between 14:00 on 14 November and 15:00 on 15 November 2018. In each of Experiment and Control, five and ten roots of the cultured mini-bok choy were collected randomly at the start (8 November 2018) and at the end of the experiment (30 November 2018), respectively. Their fresh weights of the aerial part and root were weighed.

The statistical significances of the correlations between the elapsed time and the DO of the nutrient solution of the pool in Experiment in five different periods between 14:00 on 14 November and 15:00 on 15 November 2018 were tested by Pearson's correlation coefficient, and the differences of the fresh weights of the aerial part and the root of bok choy between Experiment and Control were tested by Mann-Whitney's U-test, respectively, with a computer software for Macintosh (Apple Inc., U.S.), StatView® (Ver. 4.5, Abacus Concepts, Inc., U.S.).

RESULTS

DO Fluctuations of the Nutrient Solution

We conducted a cultivation experiment of mini-bok choy with the DFT hydroponic cultivation system using a hyper-oxygenated nutrient solution, in a greenhouse (Figure 1). In the daytime, the DO of the nutrient solution in "Experiment" was kept in hyper-oxygenated conditions with 16.7 to 21.7 mgO_2 L^{-1} due to the aeration of pure oxygen micro-bubbles, while that in "Control" with no aeration system was restricted in the unsaturated range between 1.7 and 4.2 mgO_2 L^{-1} throughout the period of the experiment (Figure 2). During the nighttime, a dynamic fluctuation of DO of the nutrient solution was observed in Experiment. The observation of DO of the nutrient solution between 14:00 on November 14 and 15:00 on November 15 in 2018 shows a typical example (Figure 3).

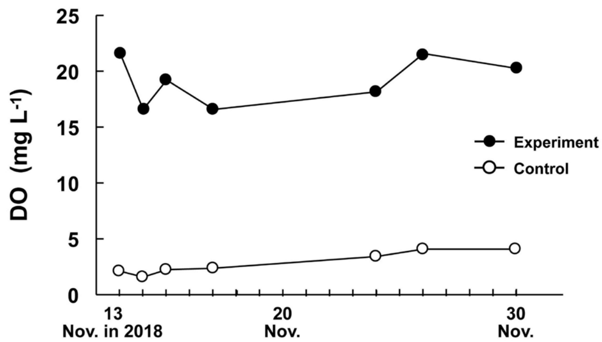

Figure 2: The changes of DO of the nutrient solution of the pools measured in the daytime (13:00 to 15:00) in the DFT hydroponic cultivation system of mini-bok choy used for the experiment during the period of the experiment between 13 November and 30 November 2018.

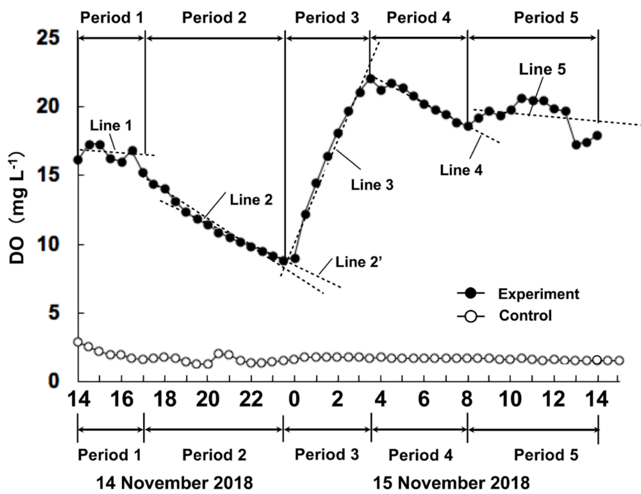

Figure 3: A typical example of the diurnal DO fluctuations monitored every thirty minutes between 14:00 on 14 November and 15:00 on 15 November 2018. They were divided into five different periods (Period 1 to Period 5), and a regression line was interpolated to the data plots in each of the five periods.

The DO of the nutrient solution fluctuated between 8.85 and 22.06 mgO_2 L^{-1} during this period, and was characterized by five different periods (Period 1 to Period 5) (Figure 3, Table 1). In Period 1 and Period 5, the DO of the nutrient solution had decreased gently at the ratios of -0.09 mgO_2 L^{-1} h^{-1} and -0.17

$mgO_2\ L^{-1}\ h^{-1}$, respectively. This phenomenon can be regarded partly due to a natural loss of oxygen gas to the ambient air. In contrast, a rapid decrease of DO of the nutrient solution was observed between 17:00 and 23:00 in Period 2 (-0.96 $mgO_2\ L^{-1}\ h^{-1}$) and between 03:30 and 8:00 in Period 4 (-0.78 $mgO_2\ L^{-1}\ h^{-1}$), respectively. In Period 3 between 23:30 and 03:30, the nutrient solution was aerated with pure oxygen micro-bubbles released by the two sets of micro-bubble generators at the gas flow rate of 1.4 L min^{-1} (in total) to keep the hyper-oxygenated conditions. The DO of the nutrient solution increased at the rate of +3.59 $mgO_2\ L^{-1}\ h^{-1}$. If additional DO was not supplied to the nutrient solution in this period, its DO seemed to have decreased to almost the same level as Control until 8:00 on November 15, judging from the decreasing DO rates in Period 2' and Period 4. In Control, the nutrient solution was under hypoxic conditions (1.50 to 2.55 mg L^{-1}) throughout this period. During the nighttime, no alternative source of oxygen was available for the root of the crop.

Line No.	Time	Temper-ature (°C)	Slope ($mgO_2\ L^{-1}\ h^{-1}$)	R^2	P
1	14:00 to 16:30	18.1 to 17.9	-0.09	0.023	0.793
2	17:00 to 23:30	17.9 to 16.0	-0.96	0.955	<0.0001
2'	19:00 to 23:30	17.2 to 16.0	-0.77	0.992	<0.0001
3	23:30 to 03:30	16.0 to 15.6	3.59	0.98	<0.0001
4	03:30 to 08:00	15.6 to 14.7	-0.78	0.951	<0.0001
5	08:00 to 15:00	14.7 to 17.2	-0.17	0.128	0.194

The regression line 2' was calculated with the DO data of the nutrient solution between 19:00 and 23:30 on 14 November 2018 in Period 2.

Table 1: The effect of hyper-oxygenation of the nutrient solution on the growth of mini-bok choy in Experiment and requirements for the experiment over 23 days.

Timing of Critical Points of DO Fluctuations

These diurnal changes of the DO of the hyper-oxygenated nutrient olution in Experiment indicate the presence of critical points in oxygen transmission from the shoot to the root and intake of DO of the solution through the root at 17:00 in November 14 and 8:00 on November 15. According to the weather report at the nearest local meteorological observatory, the critical points had come when the total solar radiation decreased to 0.47 MJ m^{-2} at 17:00, and then increased to 0.36 MJ m^{-2} at 8:00, respectively[20] (Figure 4). The timing of these critical points was just coincidental with the dim periods at twilight and dawn, respectively. Hence, we are able to explain this as the cultivated crop potentially possesses a function to take in DO of the solution through the root if ample DO is contained in it, and its switch is turned on when the solar radiation has decreased to the levels unsuitable for photosynthesis. It is turned off when it has increased to the intensity strong enough for photosynthesis even if the nutrient solution is hyper-oxygenated.

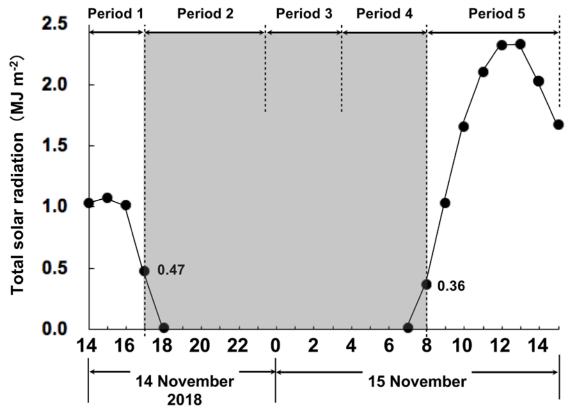

Figure 4: Diurnal changes of the total solar radiation observed at the nearest meteorological observatory (Kumamoto Local Meteorological Observatory) to the experimental site, which is about 10 km apart, between 14:00 on 14 November and 15:00 on 15 November 201820. The darks area indicates the period that enough light intensity was not available for photosynthesis by the mini-bok choy cultivated in this study.

Growth of Mini-bok Choy

The differences of the DO conditions of the nutrient solution between Experiment and Control were reflected as those of the crop growth for 23 days in the experiment (Figure 5). The fresh weights of the seedlings in Experiment and Control were 2.14 ± 0.31 g and 2.17 ± 0.68 g in the aerial parts (mean ± S.D., n=5), and 0.45 ± 0.03 g and 0.46 ± 0.14 g in the root (mean ± S.D., n=5), respectively. Both fresh weights of the aerial part and root showed no significant difference between them (Mann-Whitney's U-test, aerial parts: P=0.917, n=5; roots: P=0.602, n=5). After cultivation for 23 days, the fresh weights of the aerial parts and root grew to 20.34 ± 8.09 g and 3.10 ± 1.16 g (mean ± S.D., n=10) in Experiment, while growth in Control was restricted to 10.23 ± 3.79 g and 1.82 ± 0.55 g (mean ± S.D., n=10), respectively. The differences of the fresh weights of both of the aerial parts and root were statistically significant between Experiment and Control (Mann-Whitney's U-test, aerial parts: P<0.001, n=10; roots: P=0.019, n=10). Figure 6 compares the whole images of the individuals which are closest o the mean fresh weight of the aerial parts and root in Experiment and Control at the end of the experiment. It is obvious that the increase of oxygen intake through the root during the nighttime brings a remarkable promotion of crop growth (approximately 2.0 and 1.7 folds of the growth acceleration of the aerial parts and root to Control, respectively).

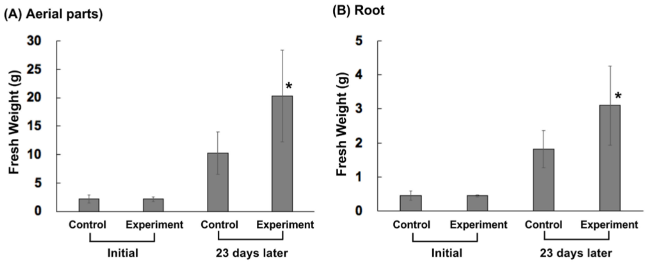

Figure 5: Fresh weights of the mini-bok choy cultured in the DFT hydroponic cultivation system in the experiment. (a) aerial parts, (b) root. Bars indicate the standard deviations. The asterisks indicate the statistically significances of the values of Experiment to those of Control.

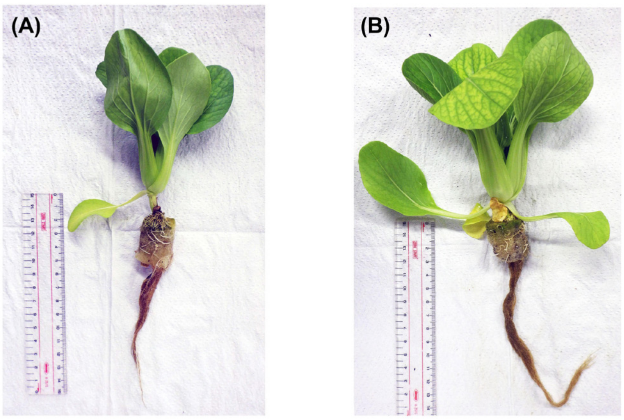

Figure 6: Images of the mini-bok choy most close to the mean fresh weight of the aerial parts and root in (a) Control (aerial parts: 10.45g (mean:10.23 g), root: 1.88 g (mean: 1.82 g), and (b) Experiment (aerial parts: 20.71 g (mean: 20.34 g), root: 2.60 g (mean 3.10 g)) after 23 days from the start of the cultivation experiment.

DISCUSSION

The Mechanisms of the Physiological Responses of the Crop to the Hyper-Oxygenated Nutrient Solution

In this study, the results of the cultivation experiment of mini-bok choy in the DFT hydroponic cultivation system demonstrate that oxygen intake through the stomata on the leaves hardly contributes to the oxygen transmission to the root during the nighttime when the internal oxygen production by photosynthesis has stopped, but it can rely on the DO of the nutrient solution as an alternative oxygen source to the root if they DO of the nutrient solution is in the range between 8.85 and 22.05 $mgO_2\ L^{-1}$ (DO saturated or hyper-oxygenated conditions). However, the oxygen intake of the root stops when the solar radiation has increased to intensity strong enough for photosynthesis even if the nutrient solution is hyper-oxygenated. (Figures 3 and 4). These facts reveal an unknown capacity of the root of mini-bok choy with two ways of oxygen intake, responding to the light intensity. This capacity seems to be applicable for a wide variety of crops, but it tends to be concealed since oxygen is much less diffusible and soluble to the water under the present atmosphere of 1 atm that contains about 21% of oxygen.

Is the Micro-Bubble Technique for Aerating the Nutrient Solution Cost-Beneficial?

The previous DFT hydroponic cultivation experiments, with the nutrient solution aerated by air micro/nano-bubbles, created DO saturated levels slightly higher than those of the control (max. 0.3 to 1.2 $mgO_2\ L^{-1}$), and have already demonstrated a significant promotion of increase in the fresh weight of the aerial part of rape (about 1.3 times greater, 28 days) [17], spinach (about 1.4 times greater, 21 days) [18], and Cos lettuce (Romaine lettuce, *Lactuca sativa* L. var. *longifolia*) (about 2.1 times greater, 14 days later) [19], respectively, although they did not present the mechanisms of growth promotion. However, all experiments were conducted in small tanks or containers with only 70 to 125 L of the nutrient solution [17-19]. If these aeration systems that use ambient air are introduced to the DFT hydroponic cultivation of the crops in actual greenhouses for horticulture, it will be hard to sustain a large amount of oxygen demand of the crops or a large-size aeration device and a large-capacity of power will be required to balance with the DO demand of the crops during the nighttime.

In the present study, we conducted the cultivation experiment of mini-bok choy in a pool for the DFT hydroponic cultivation actually used for the horticultural activity, aerating about 1.25 m^3 of the nutrient solution with pure oxygen micro-bubbles released from two sets of small micro-bubble generators for four hours in a day, and realized approximately 2.0 and 1.7 folds of the growth acceleration of the aerial part and root to those of Control, respectively (Figure 5). Nevertheless, this experiment was characterized by extremely small power consumption for aeration, 3.16 kWh (395W x 2 x 4 (h)), and only 360 L of pure oxygen gas consumption (0.75 L ($min.^{-1}$) x 2 x 60 (min.) x 4 (h)) per night, due to an extremely high dissolution capacity of pure oxygen micro-bubbles to the nutrient solution. 360 L of pure oxygen gas weighs 489.4 g. In the aeration of the nutrient solution in Experiment for four hours between 23:30 on 14 November and 3:30 on 15 November 2018 (Figure 3), 221.5 g O_2 stock of the nutrient solution increased as DO. Therefore, 45.3% of 360 L of pure oxygen gas released as micro-bubbles dissolved into the nutrient solution in the pool of the DFT cultivation system in Experiment in this period.

However, this efficient aeration method for the nutrient solution with pure oxygen micro-bubble still does not seem to be cost-effective enough to introduce it to the actual hydroponic cultivation of the crop in a greenhouse, although it realized approximately 2-folds of accelerated growth of the crop in Experiment in this study (Figure 5). Table 2 concludes the effect of hyper-oxygenation of the nutrient solution on the growth of mini-bok choy in Experiment and displays requirements for the experiment over 23 days. We estimated that the total weight of the crop in Experiment increased by 9,734 g to Control, but the increase of the sales amount of the crop by the growth acceleration seems to be almost in balance with the total cost of power consumption (72.68 kWh) and 8,280 L of pure oxygen gas spent for aeration of the nutrient solution.

	Control	Experiment
[Growth]		
Weight of seedling (g $root^{-1}$)	2.17 ± 0.68*	2.14 ± 0.31*
(after 23 days)		
Weight of aerial part (g $root^{-1}$)	10.23 ± 3.79*	20.34 ± 8.09*
Mean weight increase of aerial part (g $root^{-1}$)	8.06	18.2
Total weight increase of 960 roots (g) in a pool	7,738	17,472
Acceleration of growth in Experiment (g per 960 roots)		9,734
[Power and gas consumption]		
Consumption of power for aeration (kWh d^{-1})	none	3.16
Total consumption for 23 days (kWh)	none	72.68
Consumption of pure oxygen gas (L d^{-1})	none	360
Total consumption for 23 days (L)	none	8,280
* mean ± S.D., n=10		

Table 2: The effect of hyper-oxygenation of the nutrient solution on the growth of mini-bok choy in Experiment and requirements for the experiment over 23 days. * mean ± S.D., n=10.

A Solution to Minimize the Cost for Hyper-Oxygenation of the Nutrient Solution

The nutrient solution can be hyper-oxygenated by replacing pure oxygen gas with 90% oxygen gas produced by an "oxygen concentrator", which has been used for oxygen therapy for humans. For example, one set of the small one that runs with 290W of power can produce 5 L $min.^{-1}$ of 90% oxygen gas with cost-free ambient air, and can provide gas at the same gas flow rate (0.75 L $min.^{-1}$) as the experiment in this study to at least six sets of the micro-bubble generators used in the experiment. Furthermore, oxygen concentrators have been disposed of after patient use for several years at least in Japan (and presumably in various countries with advanced medical care systems), but it can still produce useful oxygen gas with a concentration of 90% or slightly less. In our preliminary tests, another type of micro-bubble generator, which is made up of a submersible pump with 250W of power consumption and nozzle for releasing micro-bubbles, could make 1 m^3 of the hyper-oxygenated water containing about 30 mgO_2 L^{-1} of DO from tap water in a tank within one hour, being supplied with about 90% oxygen gas from "an used oxygen concentrator" at a gas flow rate of 0.75 L min^{-1}. Therefore, the combined use of the micro-bubble generator along with the used oxygen concentrator enables us to minimize the installation cost to use 90% oxygen gas and the running cost for preparing the hyper-oxygenated nutrient solution for hydroponic cultivation of the crop.

We have already tested this new aeration method with the nutrient solution for the DFT hydroponic cultivation of other leafy vegetables such as lettuce, spinach, basil, and parsley, and cultivation of flowers in pots with soil such as cyclamen and phalaenopsis orchid, and we have commonly confirmed a significant acceleration of growth. The results of the experiments will be reported elsewhere. This method seems to be applicable to the cultivation of a wide variety of crops and plants for horticulture, and brings a remarkable acceleration of growth and/or increase of production just by suppling hyper-oxygenated nutrient solution or water as if it was done in grain production by breed improvement in the 1940s to 1960s referred to as "Green Revolution" [21,22].

CONCLUSION

The results of the cultivation experiment of a test crop for hydroponic cultivation with the DFT hydroponic cultivation system, mini-bok choy, revealed its unknown basic capacity for oxygen intake of the root, responding the changes of light intensity. It can rely on the DO of the nutrient solution as an alternative oxygen source to the root when the internal production of oxygen production by photosynthesis has stopped, if ample oxygen is dissolved in the nutrient solution. However, the oxygen intake of the root does not run in the light conditions enough for the photosynthesis even if the nutrient solution is hyper-oxygenated. Mini-bok choy, cultivated in the pool with hyper-oxygenated nutrient solution aerated by oxygen micro-bubbles, exhibited approximately 2.0 and 1.7 folds of the growth acceleration of its aerial part and root in the period of the experiment over 23 days, respectively, to those of Control without any aeration of the nutrient solution. The micro-bubble generator used for the experiment realized an extremely high dissolution rate of oxygen gas, 45.3%, to the nutrient solution, and its combined use with an oxygen generator enables us to minimize the cost for creating hyper-oxygenation of the nutrient solution, and to realize a dramatic acceleration of the growth of the crop.

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