Effects of the Circulation Pump Type and Ultraviolet Sterilization on Nutrient Solutions and Plant Growth in Plant Factories

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ADDITIONAL INDEX WORDS. Fe ions, hydroponics, ion concentration, lettuce, strawberry, UV

SUMMARY. Hydroponic systems in plant factories can be categorized into recirculating or noncirculating systems. In this study, the effects of various commercially available circulation pumps, including a centrifugal magnetic drive pump, a regenerative self-priming pump, and a submersible pump, were experimentally explored. In addition, the effects of an ultraviolet sterilization system on the ion concentrations in nutrient solutions were examined. The concentrations of sodium, potassium, magnesium, calcium, nitrate, sulfate, and ferric (Fe^{3+}) ions in the nutrient solution were measured. For all three types of pumps, the results indicated that there was no significant effect on the concentrations of ions in the nutrient solution. However, the concentration of Fe^{3+} ions decreased significantly after the nutrient solution was treated by a ultraviolet sterilization system for 48 hours. In addition, the effects of the three types of pumps on the growth of butterhead lettuce (*Lactuca sativa*) were examined. The temperature records during the pump circulation tests showed that the nutrient solution temperature of the regenerative self-priming pump increased by 15.5 °C (from 20.5 to 36 °C), which caused yellow seedling, scorching on the leaves, and browning of the roots. The ion concentration in the nutrient solutions and total fresh weight of butterhead lettuce did not show any noticeable difference between the centrifugal magnetic drive pump and the submersible pump. In this paper, we clarify the cause of the decreasing iron concentration and provide a guideline for selecting the pump for circulating hydroponic systems in plant factories.

Crops grown outdoors are declining in quantity and quality because of worsening problems related to climate change and environmental deterioration (Fischer et al., 2002; Nelson et al., 2009; Rosenzweig and Liverman, 1992). Food security has become an increasingly important issue in recent years, and plant factories are considered possible solutions to food crop cultivation problems. In addition, the cultivation of fresh vegetables in dry climate areas or nonseasonal vegetables has become feasible in plant factories (Castilla and Hernandez, 2006; Wilson et al., 1992).

A plant factory is an enclosed plant-growing space that is typically equipped with cultivation racks, an air-conditioning system, a hydroponic system, and light-emitting diode (LED) or fluorescent lighting (Ikeda et al., 1992). This type of facility enables for the precise control of a cultivation environment in terms of irradiance, temperature, humidity, carbon dioxide concentration, and composition of the nutrient solution (Kozai et al., 2015; Yamori et al., 2014), which produces plants with minimal quality difference and in

predetermined numbers. Moreover, the produce from the plant factory is cultivated without the use of pesticides and with minimal amounts of bacteria; therefore, it is edible without having to be washed. Plant factories also use a multilayered cultivation system to increase space efficiency (Despommier, 2009). In such a facility, the vertical closed cultivation system (which features the use of multilayer cultivation racks) coupled with favorable cultivation conditions that improve the turnover rate of plants helps to boost plant productivity per unit area (Goto, 2012; Kato et al., 2011).

However, the primary problem that plant factories currently face is high energy consumption. With the advent of red and blue LED lights, the energy consumption of plant factories equipped with artificial lighting has decreased, but lighting still accounts for ≈80% of their electricity costs (Kozai, 2007). Thus, unless the factories are designed to be more energy-efficient, their products are unlikely to become competitive in price. The production cost is always a concern for a plant factory operation.

Hydroponics is a plant cultivation method primarily implemented in plant factories. The method involves using nutrient solutions instead of soil to grow plants. Compared with soil-based cultivation, hydroponics requires less water and fewer nutrients and enables efficient control of environmental factors (Jones, 2016). Hydroponic systems can be divided into recirculating and noncirculating types, depending on how they supply water and nutrients. One limitation of non-circulating hydroponic systems is that they discharge 15% to 40% of their nutrient solutions, which can cause

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Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
38.6807	fl oz/yd ³	mL·m ⁻³	0.0259
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
25.4	inch(es)	mm	0.0394
41.8410	langley(s)	kJ·m ⁻²	0.0239
1	mmho/m	mS·m ⁻¹	1
28.3495	oz	g	0.0353
1	ppm	mg·kg ⁻¹	1
1	ppm	mg·L ⁻¹	1
10.7639	W/ft ²	W·m ⁻²	0.0929
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32
(°F ÷ 1.8) + 255.37	°F	K	(K – 255.37) × 1.8

Fig. 1. Centrifugal magnetic drive water pump (A), regenerative self-priming pump (B), and submersible water pump (C) used to study their effects on the ion concentration of nutrient solutions.

environmental problems, such as eutrophication and resource waste (Benoit, 1992; Sonneveld, 1993). Consequently, recirculating hydroponic systems are required to reduce the costs and problems associated with the discharge of water and nutrients.

Recirculating hydroponic systems return the nutrient solutions that are not absorbed by the plants to a holding tank. Measurements of the ion consumption in the nutrient solution help to determine how much water and nutrients are absorbed by the plants. A typical recirculating hydroponic system to facilitate the cultivation of leaf vegetables is the deep flow technique (DFT) hydroponic system (Ikeda, 1985; Suzuki et al., 1984). A holding tank directly below

Table 1. Composition of full-strength Enshi strawberry nutrient solution and Yamazaki lettuce nutrient solution.

Element	Enshi concn (mg·L ⁻¹) ^a	Yamazaki concn (mg·L ⁻¹)
Nitrogen	245.8	92.2
Phosphorus	41.8	15.4
Potassium	312.5	156.2
Calcium	161.3	40.1
Sulfur	65.4	16.1
Magnesium	49.3	12.1
Iron	3.8	2.4
Sodium	1.6	1
Boron	0.52	2.8
Manganese	0.46	0.14
Zinc	0.05	0.02
Copper	0.012	0.01
Molybdenum	0.008	0.0052

^a1 mg·L⁻¹ = 1 ppm.

the planting bed can hold a large volume of nutrient solution and includes a pump to continuously or intermittently circulate the solution to ensure proper mixing.

In a closed recirculating hydroponic system, the composition of the nutrient solution tends to change over time (Cloutier et al., 1997; Son and Takakura, 1987; Zekki et al., 1996). For example, when a potato plant (*Solanum tuberosum*) absorbs potassium ions (K⁺) in large quantities from the nutrient solution, the amount of K⁺ in the solution can decrease to a notably low level (Fong and Ulrich, 1969), which is often accompanied by the accumulation of calcium ions (Ca²⁺) in the solution (Chang et al., 2011). Consequently, the ratio of K⁺ to Ca²⁺ rapidly decreases in the nutrient solution, which may cause nutritional disorders in the plants. Moreover, when exudates from the plant roots accumulate in a nutrient solution, these self-produced toxins (e.g., benzoic, phthalic, and sinapic acids) can damage the plants (Jung et al., 2004; Ortega et al., 1996; Yu and Matsui, 1993), restrict the oxygen supply to the roots, and inhibit their growth (Gislerød and Kempton, 1983).

Generally, hydroponically grown crops are less likely to be contaminated with pathogens than soil-grown crops. However, whenever a plant is contaminated, pathogens can rapidly spread through the nutrient solution to neighboring plants. To prevent pathogen transmission in hydroponic systems, filters, heat, ozone, or/and ultraviolet sterilization

systems are commonly used. For example, a 254-nm ultraviolet sterilization system is efficient at eliminating pathogens, which can be eliminated from a nutrient solution at an irradiance of >2.5 kJ·m⁻² (Runia, 1993).

In a joint research project with the Department of Horticulture and Landscape Architecture at National Taiwan University (Taipei, Taiwan), ‘Toyonoka’ strawberry (*Fragaria ×ananassa*) was grown in a DFT hydroponic system in the university’s plant factory. There, the strawberry often stopped growing and exhibited severe physiological disorders after 2 weeks. In addition to the accumulation of exudates from the roots of certain plants, other factors might severely hinder the growth of the strawberry (Hung, 2013). It was unclear whether the submersible pump to circulate the nutrient solution or the ultraviolet sterilization for the nutrient solution installed in the system accounted for this result.

In this study, the effects of various types of commercially available circulation pumps on the ion concentrations in nutrient solutions and growth of butterhead lettuce were examined. The effect of a ultraviolet sterilization system on the ions in the solution was also investigated.

Materials and methods

NUTRIENT SOLUTION CIRCULATION TEST SYSTEM. The experiment was conducted in June 2017 at the Mass and Energy Transfer Laboratory of the Department of

Fig. 2. Flow chart of nutrient solution and butterhead lettuce growth experiments. Ca^{2+} = calcium; Fe = iron; K^+ = potassium; Mg^{2+} = magnesium; Na^+ = sodium; NO_3^- = nitrate; SO_4^{2-} = sulfate; UV = ultraviolet.

Fig. 3. Absorbance (AU) of full-strength Enshi strawberry nutrient solution at each dilution rate over the 390- to 700-nm waveband. The photometric accuracy of spectrophotometer was ± 0.005 absorbance.

Bio-Industrial Mechatronics Engineering, National Taiwan University, and the university's plant factory.

Three circulation pumps were tested in a series of experiments that did not involve plant production, including a 110-W centrifugal magnetic drive pump (HCM-75LX; UNO Corp., Taichung, Taiwan) (Fig. 1A),

a 373-W regenerative self-priming pump (KP320NT; Kikawa Corp., Taoyuan, Taiwan) (Fig. 1B), and a 60-W submersible pump (HP-3500; Ming-Zen Corp., Taichung, Taiwan) (Fig. 1C). A 15-W ultraviolet sterilization system developed by ISTA Corporation (Tainan, Taiwan) was also used and tested. During

the experiment, full-strength Enshi strawberry nutrient solution (Hori, 1966) was circulated for 5040 min (84 h) with an initial volume of 20 L and a flow rate of $800 \text{ L} \cdot \text{h}^{-1}$. Sampling was conducted once per 720 min (12 h), and eight samples were collected in total. Before sampling, the solution was refilled with deionized (DI) water to its initial level to compensate for any evaporation-induced losses. In addition, a $100 \times$ full-strength Enshi strawberry nutrient solution was stored in a beaker and irradiated by a 254-nm ultraviolet sterilizer (209b; CCIBeauty, Santa Fe Springs, CA) for 5000 min to observe the Fe precipitation; the ultraviolet C (UVC) intensity emitted from the ultraviolet sterilizer was $\approx 30 \text{ W} \cdot \text{m}^{-2}$. The salts required to prepare 1 L of full-strength Enshi strawberry nutrient solution are listed in Table 1. The series of experiments of the nutrient solution circulation test system is shown in Fig. 2.

MEASUREMENTS OF THE CONCENTRATION OF IRON (Fe) IONS IN THE ENSHI STRAWBERRY NUTRIENT SOLUTION. A testing system for Fe ions (#114759 Iron Test; Merck, Darmstadt, Germany) was used to collect samples of 6 mL from the nutrient solution; three drops of

Fig. 4. Relationship between the measured absorbance (AU) of full-strength Enshi strawberry nutrient solution and dilution rates ($y = 1.1243x + 0.0719$, $R^2 = 0.9866$).

Fig. 5. Time series of iron ion absorbance (AU) at 561 nm of full-strength Enshi strawberry nutrient solution after circulation tests through a regenerative self-priming pump, centrifugal magnetic drive pump, submersible pump, and ultraviolet (UV) sterilization system. Samples were obtained every 12 h.

reagent were added to the samples. The solution and reagent were sufficiently mixed and reacted with each other for 3 min. In this mixture, all ferric (Fe^{3+}) ions were reduced to ferrous (Fe^{2+}) ions. All Fe^{2+} ions subsequently reacted in a thioglycolate-buffered medium with a triazine derivative to form a red-violet complex. Then, a spectrophotometer (PRO7990; Chuan-Hua Corp., New Taipei City, Taiwan) was used

to measure the absorbance of the sample across the wavelength range of 200 to 800 nm.

ANALYSIS OF MAJOR IONS IN THE ENSHI STRAWBERRY NUTRIENT SOLUTION. The sample was diluted 20 times, and an ion analyzer (IA-300, cationic column PCI-205, anion column PCI-322; DKK-TOA Corp., Tokyo, Japan) was used to examine the change in cations [sodium (Na^+), K^+ , magnesium (Mg^{2+}), and

Ca^{2+}] and anions [nitrate (NO_3^-) and sulfate (SO_4^{2-})] in the sample. The IA-300 ion analyzer is a small-footprint dedicated chromatograph to measure a predefined number of ions. It can quickly and easily measure six cations or seven anions in many types of samples.

EXPERIMENTS FOR THREE DIFFERENT CIRCULATION PUMPS TO GROW BUTTERHEAD LETTUCE. A closed plant factory (spanning an area of 15.95 m^2) in National Taiwan University was used from Apr. to July 2017, where the temperature setting was 20°C at night and 25°C during the day, and the carbon dioxide (CO_2) concentration was $550 \text{ mL}\cdot\text{m}^{-3}$.

Seeds of butterhead lettuce were germinated and grown for 15 d. Specifically, they were grown using pure water for the first 5 d in the nursery and using a full-strength Yamazaki nutrient solution for the remaining 10 d (Yamazaki, 1982). During the nursery period, the photoperiod was 24 h.

After the completion of the germination period, the butterhead lettuce seedlings were shifted into a 30-L plastic container (1100 mm long, 700 mm wide, and 90 mm high), and a polystyrene foam floating board ($1070 \times 520 \times 30 \text{ mm}$) was placed on top of the nutrient solution. The plant roots were inserted into the nutrient solution, and the shoots protruded above the foam board. Twelve butterhead lettuce seedlings were planted on each tray, and two trays of seedlings were placed in two shelves of a rack. The growth period was 20 d with a daily photoperiod of 16 h.

During the 20-d growth period, one of three circulation pumps was tested and used to circulate the nutrient solution. The other two pumps were tested in other new growth periods. The nutrient solution tank was 90 L in capacity. Each of the two water trays was 30 L in capacity. The total amount of nutrient solution was 150 L. The solution was full-strength Yamazaki's lettuce nutrient solution with an initial electrical conductivity of $110 \text{ mS}\cdot\text{m}^{-1}$, and sodium hydroxide (NaOH) or sulfuric acid (H_2SO_4) was used to adjust the pH value (WM-32EP; TOA-DKK Corp., Tokyo, Japan) to 6. The flow rate of the nutrient solution was controlled

through valves in the supply lines to the pumps at 2800 L·h⁻¹. After 35 d of cultivation, the butterhead lettuce plants were harvested, and their total fresh weight, total dry weight, and nitrate concentrations (through a nitrate test) were measured. Each recirculating system had two replicates, and each replicate had 24 plants. The salts required to prepare 1 L of full-strength Yamazaki nutrient solution are listed in Table 1. The series of experiments of growing butterhead lettuce is shown in Fig. 2.

LIGHT SOURCE. Twenty-eight-watt T5 fluorescent tubes (Welly-power, Hsinchu, Taiwan) with a color temperature of 6500 K were used to irradiate the plantlets with an average photosynthetically active radiation (PAR) intensity of 250 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The intensity was measured by a calibrated PAR meter (LI-250A; LI-COR, Lincoln, NE).

NO₃⁻ CONCENTRATION MEASUREMENT. NO₃⁻ ions were reduced to nitrite ions using a reducing agent. With an acidic buffer, these nitrite ions reacted with an aromatic amine to form a diazonium salt, which subsequently reacted with N-(1-naphthyl)-ethylene-diamine to form a red-violet azo dye that was measured by ultraviolet reflectometry (#116971 Nitrate Test; Merck, Darmstadt, Germany).

STATISTICAL ANALYSIS. The Excel (Microsoft Corp., Redmond, WA) software suite was used for experimental analysis. Two recirculating systems had two replicates, and each replicate grew 24 plants. There were 24 plants in a batch of experiments. Twenty of them were selected to measure the total fresh weight, total dry weight, and tissue NO₃⁻ concentration and thereafter statistics ($n = 20$). The significance of differences was compared using the t test at the 95% confidence level.

Results

Nutrient solution circulation test system

MEASURING THE CONCENTRATION OF Fe IONS IN THE ENSHI STRAWBERRY NUTRIENT SOLUTION. Full-strength Enshi strawberry nutrient solution was diluted and reacted with the iron test reagent. The absorbance of the solution at dilution rates of 1 (100% solution),

0.8, 0.6, 0.4, 0.3, 0.2, 0.1, and 0 (pure water) was measured using a spectrophotometer; the measurement results are shown in Fig. 3. The results indicate that before the dilution, the Enshi strawberry nutrient solution had an Fe ion concentration of 3.8 mg·L⁻¹ and an absorbance of 1.13 at a local peak wavelength of 561 nm. Notably, the measured absorbance of the nutrient solution is linearly related to its dilution rate (Fig. 4).

The spectrophotometer was also used to examine the changes in absorbance of the nutrient solution every 12 h after the circulation tests with a regenerative self-priming pump, a centrifugal magnetic drive pump, a submersible pump, or the ultraviolet sterilization system (Fig. 5). The results indicate that the three pumps had no apparent effect on the Fe content of the nutrient solution. After the circulation with one of the three pumps, all three nutrient solutions maintained the absorbance of ≈ 1 at a wavelength of 561 nm.

In contrast, the absorbance of the nutrient solution noticeably changed after a circulation test with the ultraviolet sterilization system driven by a submersible pump. After the nutrient solution was circulated by the system for 24 h, its absorbance decreased from 1 to 0.2; after another

24 h of circulation, it further decreased to 0.1. Furthermore, the 100 $\times$ full-strength Enshi strawberry nutrient solution was stored in a beaker and placed in a ultraviolet sterilizer. After the ultraviolet irradiation, precipitation was found at the bottom of the beaker (Fig. 6). The results indicate that the ultraviolet sterilization system significantly affects the Fe concentration in the nutrient solution.

ANALYSIS OF MAJOR IONS IN THE ENSHI STRAWBERRY NUTRIENT SOLUTION. The ion analyzer was used to analyze the cation and anion concentrations of full-strength Enshi strawberry nutrient solution at an interval of 12 h after the circulation tests through the regenerative self-priming pump (Fig. 7A), centrifugal magnetic drive pump (Fig. 7B), submersible pump (Fig. 7C), and ultraviolet sterilization system (Fig. 8). The results indicate that the three pumps and sterilization system have no significant effect on the concentrations of major ions in the solution, particularly the cations Na⁺, K⁺, Mg²⁺, and Ca²⁺ and anions NO₃⁻ and SO₄²⁻ (Table 2).

EXPERIMENTS USING THREE DIFFERENT CIRCULATION PUMPS TO GROW BUTTERHEAD LETTUCE. The plants performed poorly when the self-regenerative pump was used to

Fig. 6. Precipitation of 100X full-strength Enshi strawberry nutrient solution irradiated by an ultraviolet sterilizer [before irradiation (left), after irradiation (right) for 5000 min].

Fig. 7. Time series of selected ion concentrations of full-strength Enshi strawberry nutrient solution after a circulation tests through a regenerative self-priming pump (A), centrifugal magnetic drive water pump (B), and submersible water pump (C). Samples were obtained every 12 h. Ca²⁺ = calcium; K⁺ = potassium; Mg²⁺ = magnesium; Na⁺ = sodium; NO₃⁻ = nitrate; SO₄²⁻ = sulfate; 1 mg·L⁻¹ = 1 ppm.

recirculate the nutrient solution, so the following results are from the experiments with the other two

pumps. The ion analyzer was used to assess the changes in ion concentration of full-strength Yamazaki's

lettuce nutrient solution when the butterhead lettuce seedlings were planted with the centrifugal magnetic drive pump (Fig. 9) or submersible pump (Fig. 10). The results indicate that a 20-d circulation through both pumps induced similar changes in ion concentration of the nutrient solution. The concentrations of NO₃⁻ and K⁺ slightly decreased, whereas the concentration of SO₄²⁻ and Ca²⁺ slightly increased. In contrast, the Na⁺ and Mg²⁺ concentrations showed no noticeable change.

Regarding the harvest results of the butterhead lettuce planted with the centrifugal magnetic drive and submersible pumps (Table 3), the total fresh weight of the lettuce was 100 g, which is generally a good fresh weight in plant factories (Choi et al., 2000; Kang et al., 2013). This result suggests no significant statistical difference between the two pumps.

Moreover, the NO₃⁻ concentration in the foliage of butterhead lettuce planted with both pumps was >3024 mg·L⁻¹, which indicates that the nutrient solution was indeed absorbed through the root (Salisbury and Ross, 1992). The results show no significant statistical difference between centrifugal magnetic drive and submersible pumps.

Figure 11 shows lettuce seedlings grown using the regenerative self-priming pump. After 4 d of cultivation, the seedling exhibited noticeable yellowing and scorching on the leaves and browning on the root largely because the regenerative self-priming pump increased the temperature of the nutrient solution by 15.5 °C (compared with the increases of 2.9 and 3.7 °C induced by the centrifugal magnetic drive and submersible pumps, respectively) to 36 °C. The energy lost in friction and hydraulic losses transforms to heat, and regenerative self-priming pumps are designed to deliver their waste heat into the working fluid (Engineering ToolBox, 2006). For this study, the limited heat dissipation paths and small total water volume caused a significant temperature increase.

Discussion

NUTRIENT SOLUTION CIRCULATION TEST SYSTEM. In the literature, the ultraviolet irradiation causes the Fe concentration to decline and Fe to precipitate in the solution

(Kozai et al., 2015). Irradiated by ultraviolet light, the nutrient solution produces oxides (such as hydroxyl radicals), which make its chelated Fe destabilize, degrade, and release a Fe^{3+} ion into the solution (Acher et al., 1997). Fe^{3+} tends to bind with other compounds [e.g., oxygen (O_2), hydroxide (OH^-), bicarbonate (HCO_3^-), phosphate (PO_4^{3-}), and SO_4^{2-}] in a nutrient solution to precipitate as amorphous, water-containing Fe_2O_3 (Bolt and Bruggenwert, 1978; Kirk et al., 1990). The experimental results in this work are consistent with the findings in the literature.

EXPERIMENT USING THREE DIFFERENT CIRCULATION PUMPS TO GROW BUTTERHEAD LETTUCE. The insignificant changes in concentrations of these ions in the nutrient solution may result from the low density of the lettuce (17 plants/ m^2) in multilayer

racks in the plant factory. Therefore, the ions were absorbed by the lettuce in limited quantities.

The submersible pump costs $\approx \$46$, which is much cheaper than the centrifugal magnetic drive pump ($\approx \$116$). Because the lettuce planted with the two pumps showed no significant difference, the less expensive submersible pump is a worthy option from the perspective of production costs. Meanwhile, a regenerative self-priming pump was $\approx \$70$; however, because of the side effects of the elevated nutrient temperature, use of this pump is not recommended in the plant factory. Considering the capability and cost, the submersible pump is recommended for plant factories.

The temperature of the nutrient solution directly affects root respiration. When the temperature of the nutrient solution exceeds 29°C , root respiration is accelerated, which

decreases the content of dissolved oxygen in the solution and causes browning and limited growth in the root; a decrease in temperature of the nutrient solution leads to a significant reduction in leaf scorching (Jensen and Malter, 1995). Meanwhile, studies have shown that increasing the temperature of the root improves the production of pepper (*Capsicum annuum*) plants that are grown in a greenhouse and outdoors. When the environmental temperatures during the daytime and nighttime are 23 and 19°C , there is a 30% production increment (Gosselin, 1986), and the harm of excessively low evening temperatures is attenuated to tomatoes (Jones, 1978). Therefore, for regions with high latitudes and altitudes, regenerative self-priming pumps can be used to increase the temperature of hydroponic nutrient solutions to save on heating costs.

This study investigated and discussed the effects of the centrifugal magnetic drive pump, regenerative self-priming pump, submersible pump, and ultraviolet sterilization system on the hydroponic nutrient solutions, and it demonstrated the use of the pumps for planting butterhead lettuce. The conclusions from the findings are as follows.

First, after the nutrient solutions were circulated for 5000 consecutive min by the three pumps, their concentrations of Fe ions showed no marked variations.

Second, the concentrations of Fe ions in the nutrient solutions decreased to 20% of their initial levels after the solutions were circulated through a ultraviolet sterilization system for 24 h and fell to below 10% of the original value after another 24 h of circulation through the system. Thus, the ultraviolet sterilization system should be operated before the Fe ions are added to the nutrient solution.

Fig. 8. Time series of ion concentrations of full-strength Enshi strawberry nutrient solution after circulation tests through an ultraviolet sterilization system. Samples were obtained every 12 h. Ca^{2+} = calcium; K^+ = potassium; Mg^{2+} = magnesium; Na^+ = sodium; NO_3^- = nitrate; SO_4^{2-} = sulfate; $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

Table 2. Ion concentrations of full-strength Enshi strawberry nutrient solution after a circulation test through a regenerative self-priming pump, centrifugal magnetic drive water pump, submersible water pump, or ultraviolet sterilization system.

System ^z	Ion concn [mean $\pm$ SE ($\text{mg}\cdot\text{L}^{-1}$)] ^y					
	NO_3^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}
Regenerative self-priming pump	834.50 ± 7.77	190.75 ± 1.20	8.61 ± 0.34	300.00 ± 1.25	50.85 ± 0.27	174.95 ± 0.82
Centrifugal magnetic drive pump	1016.25 ± 13.92	216.75 ± 2.75	6.86 ± 0.12	310.75 ± 4.16	52.33 ± 0.58	177.43 ± 2.35
Submersible pump	978.25 ± 13.66	214.90 ± 6.48	6.83 ± 0.18	302.50 ± 2.99	51.23 ± 0.52	176.00 ± 1.51
Ultraviolet sterilization system	960.25 ± 8.65	208.05 ± 2.89	7.27 ± 0.13	307.50 ± 4.07	52.25 ± 0.74	179.60 ± 2.48

^zEach recirculating systems had two replicates, and samples were obtained every 12 h.

^y Ca^{2+} = calcium; K^+ = potassium; Mg^{2+} = magnesium; Na^+ = sodium; NO_3^- = nitrate; SO_4^{2-} = sulfate; $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

Fig. 9. Time series of ion concentrations of full-strength Yamazaki lettuce nutrient solution planted with a centrifugal magnetic drive pump. Samples were obtained every 4 d. Ca^{2+} = calcium; K^{+} = potassium; Mg^{2+} = magnesium; Na^{+} = sodium; NO_3^{-} = nitrate; SO_4^{2-} = sulfate; $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

Fig. 10. Time series of ion concentrations of full-strength Yamazaki lettuce nutrient solution planted with a submersible pump. Samples were obtained every 4 d. Ca^{2+} = calcium; K^{+} = potassium; Mg^{2+} = magnesium; Na^{+} = sodium; NO_3^{-} = nitrate; SO_4^{2-} = sulfate; $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

Table 3. Measurements of harvested butterhead lettuce planted with centrifugal magnetic drive and submersible pumps.

Pump system ^z	Total fresh wt (g) ^y	Total dry wt (g)	Nitrate (ppm) ^y
Submersible pump	105.36	4.69	3,024.00
Centrifugal magnetic drive pump	106.63	5.02	3,101.00
Significant ^x	NS	NS	NS

^zTwo recirculating systems had two replicates, and each replicate had 24 plants.

^y1 g = 0.0353 oz, 1 ppm = 1 mg·kg⁻¹.

^xThe significant difference at $P \leq 0.05$ was according to the t test; NS = not significant.

Third, no significant change occurred in the concentrations of major cations (Na^{+} , K^{+} , Mg^{2+} , and Ca^{2+}) and major anions (NO_3^{-} and SO_4^{2-}) in the nutrient solutions after circulation through the three pumps and ultraviolet sterilization system.

Fourth, both centrifugal magnetic drive and submersible pumps were used to plant butterhead lettuce; the concentration of ions in the nutrient solutions and the total fresh weight of the vegetables did not show any noticeable difference between the pumps. The submersible pumps do not affect the ion concentrations in the nutrient solution. Thus, both pumps can be used to circulate nutrient solutions for hydroponic systems, although the less expensive submersible pump is a more favorable choice considering cost.

Fifth, the regenerative self-priming pump increased the nutrient solution temperature of butterhead lettuce by 15.5 °C (from 20.5 to 36 °C), which subsequently caused the roots to brown and its foliage to become yellow and scorched. Therefore, this type of pump may not be suitable for hydroponic systems in which low nutrient solution temperatures are required.

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Fig. 11. Butterhead lettuce seedlings grown using a regenerative self-priming pump. The photo was taken on day 4 after the seedlings were transplanted into hydroponic systems.

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