Plant-aided Desalination System: A Preliminary Study

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KEYWORDS. **basin method, CO_2 concentration, freshwater harvesting, solar desalination**

ABSTRACT. **Although 70% of the Earth's surface area is covered with water, 97% of this water is unusable because of salinity. Challenges with existing freshwater scarcity can be mitigated by investigating methods to convert saltwater into freshwater. We developed a lettuce plant-aided solar desalination system based on the basin method to harvest fresh water. The system comprises a lettuce (*Lactuca sativa* L.) plant community, white light-emitting diodes for simulating sunlight, a thermally insulated box equipped with a cooling system, and a CO_2 gas cylinder. This system can harvest freshwater with low electric conductivity using artificial seawater with less than 20% of the specified concentration. Compared with conventional solar desalination systems based on the basin method, the proposed desalination system can harvest greater amounts of freshwater. The amount of harvested freshwater increases by decreasing the CO_2 concentration because of photosynthesis in the lettuce plant community. The results suggest that lowering the CO_2 concentration can increase the amount of harvested freshwater, which is the main objective of the desalination system. Further, the results suggest that the CO_2 concentration should be maintained at around atmospheric standard levels (approximately 500 μmol·mol^{-1}) if both the freshwater and plants are to be harvested.**

Factors such as the exponential population growth, increased economic activity, and changing dietary habits (e.g., more animal-based diets that require freshwater for their production) have led to an increasing demand for freshwater, resulting in shortages in many regions (Liu et al. 2017). Although water covers 70% of the Earth's surface area, access to freshwater is limited because of the salinity of ocean water (Ibrahim et al. 2017; Manju and Sagar 2017). Oceans account for 97% of the water on Earth (saltwater), whereas glaciers account for 2%, leaving only approximately 1% of fresh water available for consumption (Atzori et al. 2019; Food and Agriculture Organization of the United Nations 1995). If freshwater could be extracted from seawater, problems associated with its scarcity could be resolved or mitigated. Therefore, various technologies have been developed for desalinating seawater.

Desalination methods can be classified into membrane- and heat-based methods (Alkaisi et al. 2017; Elsaid et al. 2020; Prajapati et al. 2021). The membrane-based methods include reverse osmosis (RO), ion exchange, and electrodialysis, whereas heat-based methods include multistage flash (MSF) and multiple-effect distillation (MED) methods (Henthorne and Boysen 2015; Mazini et al. 2014). Currently, RO (68.7%) is the most commonly used method worldwide, followed by MSF (17.6%) and MED (6.9%) (Alkaisi et al. 2017; Bataineh 2016; Curto et al. 2021; Jones et al. 2019); however, systems based on these methods involve high investments and complex desalination processes. Consequently, solar-based desalination systems categorized as heat-based methods have been considered in recent years because of the low investment and simple desalination process (Ahmadinik et al. 2020; Al-Ismaili and Jayasuriya 2016; Chaibi 2000; El-Awady et al. 2014; Li and Zhang 2024).

Based on the geometry of the heat exchanger, solar desalination systems can be designed based on basin (Dahab et al. 2023; Sharshir et al. 2023), stepped (Abdelgaied et al. 2022), and tubular methods (Li and Zhang 2024; Samimi and Moghadam 2024). Compared with conventional desalination systems such as RO, MSF, and MED, solar desalination systems have low equipment and energy costs and involve relatively simple processes; however, they have the disadvantage of low freshwater harvesting efficiency (Chaibi 2000; Li and Zhang 2024). Currently, increasing water transfer and condensation is considered to increase freshwater harvesting efficiency using systems based on the basin and stepped methods (Ahmadinik et al. 2020; Al-Ismaili and Jayasuriya 2016; El-Awady et al. 2014). Research has also focused on systems based on the tubular method, exhibiting higher freshwater harvesting efficiencies than those of other systems (Li and Zhang 2024; Samimi and Moghadam 2024).

In this study, we focus on a solar desalination system based on the basin method because of the low investment and simple desalination processes involved. Although only water is input into the system in the basin method, we anticipate that growing plants, particularly vegetables, in desalination systems can promote water transfer and condensation through transpiration. Therefore, desalination systems can be used for growing vegetables while simultaneously improving the efficiency of harvesting freshwater. However, CO_2 concentration affects stomatal opening of plants, influencing their transpiration rate in the system (Salisbury and Ross 1991). In addition, the transpiration rate of plants is affected by saltwater concentration or saline stress (Juleel et al. 2023; Yavuz et al. 2023).

This study aims to harvest fresh water from seawater using a plant-aided desalination system based on the basin method. The water input, output, and transfer in a desalination system are determined using a prototype desalination system under different CO_2 and seawater concentrations to obtain basic information required for establishing a plant-aided desalination system based on the basin method.

Materials and methods

PLANT MATERIALS. Lettuce (*Lactuca sativa* L.; variety: Flairbell) grown in a plant factory at Osaka Metropolitan University (Ohyama et al. 2018) for 22 d was used as the model plant. The plants were allowed to grow further under a photosynthetic photon

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flux density (PPFD) of 270 μmol·m^{-2}·s^{-1} with a photoperiod of 24 h·d^{-1}, air temperature of 24 °C, relative humidity of 40%, and CO_2 concentration of approximately 400 μmol·mol^{-1} for 12 to 13 d. Subsequently, the plants were transferred to containers filled with artificial seawater for the experiments. The fresh weight, dry weight, and leaf area of the plants were 58 ± 9.5, 3.7 ± 0.63, and 1100 ± 210 cm^2, respectively [mean ± standard deviation (*SD*) of 54 plants].

Artificial seawater (Tetra Marine Salt Pro; Spectrum Brands Japan, Inc., Yokohama, Japan) at 0%, 10%, and 20% of the specified concentration was supplied to the plants. Major components of ions in the seawater at 100% of the specified concentration are listed in Table 1. In the pretest, the plants experienced severe salt stress or partial wilting of the leaves when artificial seawater was supplied at 30% of the specified concentration or higher; hence, the artificial seawater at 20% of the specified concentration or lower was used in this experiment. Each artificial seawater sample was supplemented with a commercially available nutrient salt (1/2 unit of OAT House A formula; OAT Agrio, Inc., Tokyo, Japan) to prevent fertilizer deficiency during the experiment.

Desalination system. The desalination system comprised a lettuce plant community comprising six lettuce plants, a container in which seawater was stored, a lighting system with white LEDs [HMHC300E6SV9H-RM (50X-S1); Kyoritsu Densho Co. Ltd., Osaka, Japan], a thermally insulated box (0.42 m × 0.85 m × 0.42 m), a cooling system using Peltier devices, and a CO_2 gas cylinder with a controller (Fig. 1). Further, the number of air exchanges in the box was 7.1 h^{-1}. After the plant community was placed in the box, it was constantly illuminated. Drain pans were installed at the bottom of the cooling system, and the condensed water dropped by the Peltier devices was collected in glass bottles connected using silicon tubes. CO_2 gas was supplied when the CO_2 concentration in the desalination system dropped below a set point.

Table 1. Major components of ions in the seawater at 100% of the specified concentration.

Ion	Concn (mg·L^{-1})
Chloride	19,280
Sodium	10,760
Sulfate	2,650
Magnesium	1,320
Potassium	410
Calcium	455
Carbonate/bicarbonate	205
Bromide	56
Strontium	8.8
Boron	5.6
Fluoride	1.0
Lithium	0.3
Iodide	0.24

Fig. 1. Experimental setup. Desalination system used in this experiment.

Environmental conditions inside the desalination system. During the experiment, the CO_2 concentration was set at 10, 500, 1000, and 2000 μmol·mol^{-1} by controlling the CO_2 supply every 6 h. In addition, when the setpoint was 10 μmol·mol^{-1}, the CO_2 concentration in the desalination system about reached the CO_2 compensation point because of the photosynthesis of the plants. In the desalination system, the PPFD on the tray surface was set at 600 μmol·m^{-2}·s^{-1}, and the air temperature was maintained at 25 °C. The relative humidity was not controlled.

The PPFD inside the desalination system was measured and adjusted using a photometric sensor (LI-190: LI-COR Inc., Lincoln, NE, USA). The air temperature, relative humidity, and CO_2 concentrations both inside and outside the desalination system were measured using a TR-76Ui sensor (T&D Co. Ltd., Tokyo, Japan).

Water transfer and harvest rates in the desalination system. The water input, output, and transfer in the desalination system has been presented (Fig. 2). The water transfer and harvest rates were estimated for the desalination system. After 2 h of exposure to different CO_2 concentrations, the rate of water transferred by the plants was estimated from the weight changes measured every 1 min for 4 h using an electronic balance (EK-6100i; A&D Co., Tokyo, Japan). Simultaneously, the water harvest rate was estimated from the change in the weight of the glass bottles in the desalination system.

Water quality. The electric conductivity (EC) and hydrogen ion concentration (pH) of the seawater fed and remaining in the plant containers and the water harvested from the desalination system were measured using an EC meter (LAQUA-D-210C; Horiba Advanced Techno Co., Kyoto, Japan) and a pH meter (Horiba Advanced Techno Co., Kyoto, Japan).

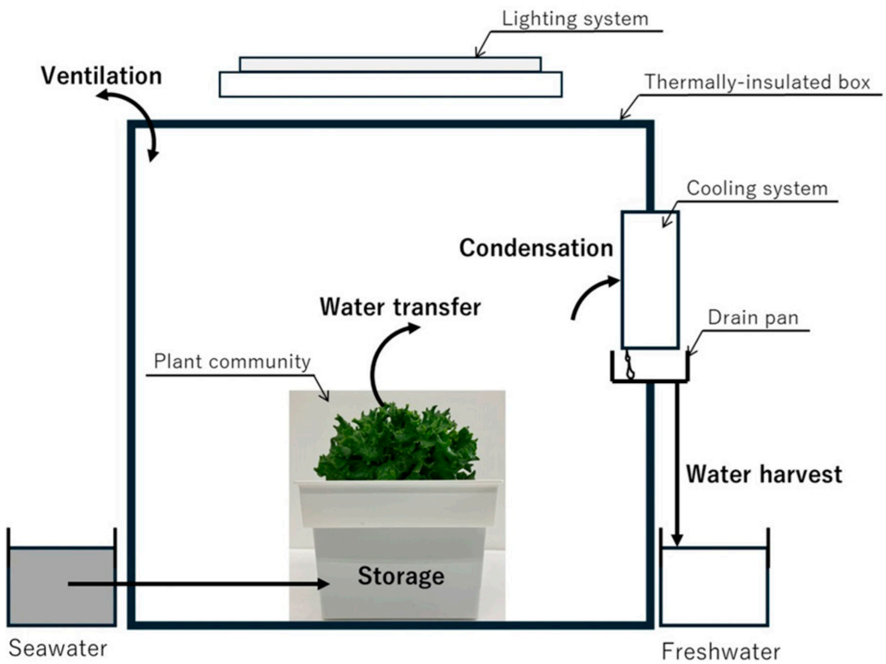

Fig. 2. Experiment procedure. Schematic showing water balance in the desalination system.

NET PHOTOSYNTHETIC RATE OF LETTUCE PLANTS. The net photosynthetic rate of the lettuce plants was estimated using the closed-assimilation box method. The plants were placed in an acrylic assimilation box (0.34 m × 0.34 m × 0.34 m), and then, CO_2 was supplied to increase the CO_2 concentration to approximately 5000 μmol·mol^{-1}. The CO_2 concentration in the closed-assimilation box was tracked once the CO_2 concentration reached 2500 μmol·mol^{-1}. The net photosynthetic rate was estimated from the change in CO_2 concentration measured at each seawater concentration.

STATISTICAL ANALYSES. Water balance and quality in the desalination system were subjected to an analysis of variance (ANOVA). For each seawater concentration, regression analyses were performed using a nonlinear model (nonrectangular hyperbola) to clarify the effect of CO_2 concentration on the net photosynthetic rate of plants. Statistical software (R version 4.3.1, R Core Team) was used for the ANOVA and regression analyses. The experiments were conducted three times at all CO_2 and seawater concentrations.

Results

ENVIRONMENTAL CONDITIONS INSIDE THE DESALINATION SYSTEM. In the desalination system, the CO_2 concentrations were controlled at 170 ± 4.7, 590 ± 21, 1100 ± 20, and 2000 ± 17 μmol·mol^{-1} (mean ± standard error) (Fig. 3A–C). PPFD was 610 ± 10 μmol·m^{-2}·s^{-1} (mean ± *SD*) in all CO_2 concentration settings. The air temperature was 25 ± 0.2 °C (mean ± *SD*), regardless of CO_2 concentration. The relative humidity was higher in seawater at 0% of the specified concentration (79% to 84%) than that at 10% and 20% of the concentration (70% to 80%).

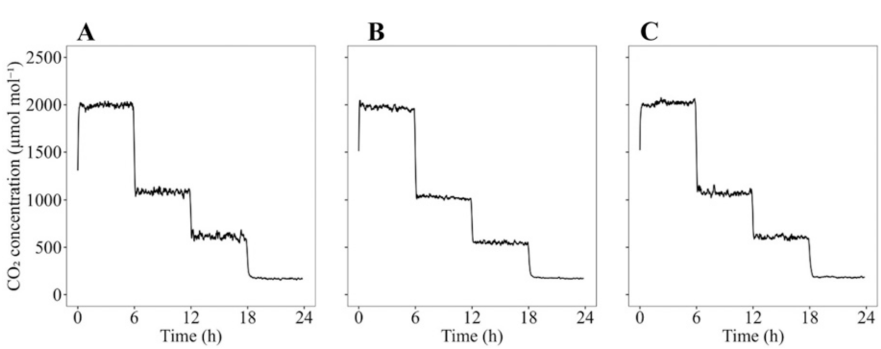

Fig. 3. CO_2 concentration in the desalination system as a function of time at 0% (A), 10% (B), and 20% (C) of the specified seawater concentration. Running averages for 10 min are shown.

WATER TRANSFER AND HARVEST RATES IN THE DESALINATION SYSTEM. For a given CO_2 concentration, the water transfer rate is 2.4 to 5.4 times greater, and the water harvest rate is 1.7 to 18 times greater in the desalination system with plants than that in the system without plants (Figs. 4A–C and 5A–C). The water transfer rate decreased with increasing CO_2 concentrations when plants were present in the desalination system (Fig. 4A–C). Further, the water transfer rate decreased with increasing seawater concentration. Likewise, the water harvest rate decreased with increasing CO_2 and seawater concentrations (Fig. 5A–C). The water harvest rate was 58% to 92% of the water transfer rate when the plants were in the desalination system (Fig. 6).

WATER QUALITY. The EC of the input seawater in the system were 1.5, 7.3, and 13 dS·m^{-1} at 0%, 10%, and 20% of the specified concentration, respectively (Table 2). The EC of the harvested water varied from 0.023 to 0.039 dS·m^{-1}. The pH values of the input seawater and harvested water were approximately 6.4 and 4.8, respectively, regardless of seawater concentration. However, the pH of the harvested water was lower than that of the input seawater.

NET PHOTOSYNTHETIC RATE OF LETTUCE PLANTS. Initially, the net photosynthetic rate of lettuce plants increased with the CO_2 concentration, regardless of the seawater concentration, and then, we began to almost saturate (Fig. 7A–C). Based on the regression curves, the net photosynthetic rates at CO_2 concentrations of 170, 590, 1100, and 2000 μmol·mol^{-1} are −0.18, 4.0, 6.1, and 7.5 μmol·m^{-2}·s^{-1}, respectively, at 0% of the specified seawater concentration. Similar results were obtained at 10% and 20% of the specified seawater concentrations.

Discussion

The water harvest rate of the desalination system decreases with an increase in salinity because of the reduced water transfer rates caused by

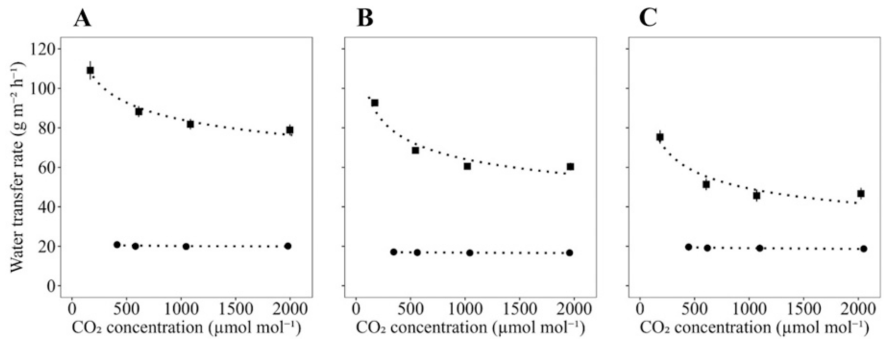

Fig. 4. Water transfer rate as a function of CO_2 concentration at 0% (A), 10% (B), and 20% (C) of the specified seawater concentration. Squares (■) and circles (●) represent mean values obtained in each condition with and without plants, respectively. Bars indicate the standard errors of the three replications.

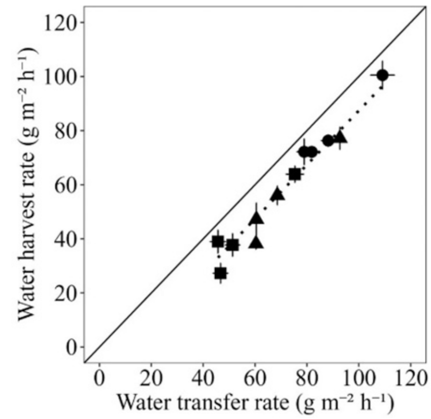

Fig. 6. Relationship between the water transfer and the harvest rates. The data were retrieved from Figs. 4A–C and 5A–C. The solid and dotted lines indicate the 1:1 and regression lines, respectively. Circles (●), triangles (▲), and squares (■) represent the mean values obtained at 0%, 10%, and 20% of the specified seawater concentrations, respectively. Bars represent the standard errors of three replications.

the lettuce plant community (Figs. 4A–C and 5A–C). The water harvest rate of the desalination system can be increased by lowering the $CO+_2$ concentration in the system. For example, at 10% salinity, lowering the CO_2 concentration to 170 μmol·mol^{-1} results in a water harvest rate equivalent to that when the CO_2 concentration is 590 μmol·mol^{-1} (near atmospheric standard level) at 0% of the specified seawater concentration (Fig. 5A and B). Photosynthesis in the plant community lowers the CO_2 concentration, and therefore, it is desirable to have a desalination system that can harvest freshwater for a short time. If the CO_2 concentration in the desalination system is not controlled, it almost reaches the CO_2 compensation point (Fig. 7A–C), possibly inhibiting the growth of the lettuce plants. However, the frequency of replanting the lettuce may decrease.

The CO_2 concentration in the desalination system should be maintained at or above atmospheric standard levels (approximately 500 μmol·mol^{-1}) to allow the lettuce plants to grow at a certain rate, as indicated by the measured net photosynthetic rate of the plants (Fig. 7A–C). The net photosynthetic rate increases with the CO_2 concentration. The water harvest rate decreases with an increase in the CO_2 concentration (Fig. 5A–C). Therefore, if the CO_2 concentration is too high (e.g., >1000 μmol·mol^{-1}), the effect of increasing the net photosynthetic rate is not significant, even though the water harvest rate decreases. This suggests that the CO_2 concentration should be maintained at close to atmospheric standard levels if the plants are to thrive and fresh water is to be harvested simultaneously.

The water transfer rate increases with a decrease in the CO_2 concentration (Fig. 4A–C) because of the increase in the transpiration rate of the plants. The transpiration rate is inversely proportional to the gas diffusion resistance between the air in the desalination system and plant leaves. Gas diffusion resistance is expressed as the sum of stomatal resistance and leaf boundary layer resistance (Monteith and Unsworth 1990). Physical environmental conditions around the plant, such as CO_2 concentration, light intensity, temperature, and air velocity, affect stomatal resistance. Further, air velocity affects the leaf boundary layer resistance (Kitaya et al. 2003). When other environmental conditions are constant, stomatal resistance decreases with decreasing CO_2 concentration because of an increase in stomatal opening (Ahmed et al. 2020; Kim et al. 2004; Li et al. 2022; Raschke 1975; Scarth 1932). Therefore, in the community of lettuce plants, transpiration rates increase under low CO_2 concentrations because of the decrease in stomatal resistance, thereby leading to a decreased gas diffusion resistance.

Water harvested via condensation in cooling systems is a reliable and stable source of water (Jurga et al. 2023). Several reports are available on water harvesting in closed systems where plants are grown (Fortson et al. 1994; Nelson et al. 1992, 2013; Salisbury et al. 1997; Tako et al. 2008; Tikhomirov et al. 2018; Xie et al. 2017; Zhang et al. 2019; Zhao et al. 2022). Reports on the water quality of the harvested water in closed systems (Mudgett et al. 1999; Ohyama et al. 2024; Zhao et al. 2022) based on EC, pH, and ion concentration are also available. In the previous studies, the EC values

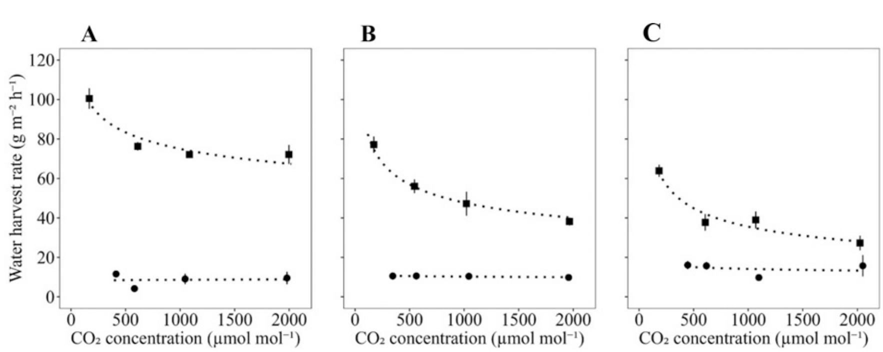

Fig. 5. Water harvest rate as a function of CO_2 concentration at 0% (A), 10% (B), and 20% (C) of the specified seawater concentration. Squares (■) and circles (●) represent mean values obtained in each condition with and without plants, respectively. Bars indicate the standard errors of three replications.

Table 2. Electric conductivity and hydrogen ion concentration (pH) of seawater in the desalination system.

	Specified concn		
	0%	10%	20%
Electric conductivity			
Input water	1.5 ± 0.0096	7.3 ± 0.0033	0.013 ± 0.0220
Output water	0.023 ± 0.0015	0.027 ± 0.0038	0.039 ± 0.0019
ANOVA	*	*	*
pH			
Input water	0.06.5 ± 0.0460	0.06.4 ± 0.0067	0.06.5 ± 0.0280
Output water	0.04.8 ± 0.0390	0.04.8 ± 0.0380	0.04.7 ± 0.0890
ANOVA	*	*	*

*Asterisks in the columns indicate significant differences at $P < 0.01$.
The values are represented in the form of mean ± standard deviation of the three replications. ANOVA = analyses of variance.

ranged from 0.05 to 0.3 $dS{\cdot}m^{-1}$. The obtained EC values (0.023 to 0.039 $dS{\cdot}m^{-1}$; Table 2) obtained in this study are slightly lower than the previously reported values. The pH of the harvested water is lower than that of the seawater; however, the reason for this remains unknown. It could be that certain ions present in the harvested water may have lowered the pH. Further, the determination of ion concentrations is required for identifying the reason for reduction in the pH of harvested water.

The conclusions of this study are based on short-term observations and may differ if the lettuce plant community is grown in the desalination system for longer periods. Studies examining the short- and long-term effects of salinity on the growth of lettuce plants demonstrated that growth suppression and death occur in the long term, even at salinity concentrations that have no effect on the growth of lettuce plants in the short term (Kim et al. 2008). Further, the net photosynthetic rate of lettuce plants is reduced by salinity stress (Juleel et al. 2023; Yavuz et al. 2023). Therefore, long-term experiments are necessary for understanding how desalination systems can be used more effectively.

In this experiment, the water harvest rate is approximately 58% to 92% of the water transfer rate when the plant community is in the desalination system, regardless of seawater or CO_2 concentrations (Fig. 6). The difference between the regression and 1:1 lines is caused by the ventilation of the desalination system, which allows water vapor to escape the system. The evapotranspiration and water harvest rates coincide when the desalination system is completely closed and no ventilation occurs (Ohyama et al. 2000). Therefore, ventilation must be minimized to increase the water harvest rate; however, reducing the ventilation may result in the accumulation of gases, such as ethylene, that are harmful to plants and can suppress their evapotranspiration rates and growth. In long-term experiments, a certain degree of ventilation is necessary for controlling the accumulation of gases in desalination systems.

In summary, a lettuce plant community was used as a model for harvesting freshwater using a plant-aided desalination system based on the basin method. When artificial seawater with less than 20% of the specified concentration was used, freshwater with low EC was harvested. The cultivation of plants in the desalination system yielded 1.7 to 18 times more freshwater than that in which no plants were cultivated. When water harvesting is the main objective of the desalination system, the decrease in water harvest rate caused by saline stress can be mitigated by decreasing the CO_2 concentration via photosynthesis by the plants. Further, this is expected to reduce the frequency of plant replanting. The CO_2 concentration in the desalination system should be maintained at approximately 500 $\mu mol{\cdot}mol^{-1}$ (atmospheric standard level) when both plants and water harvesting are the main objectives of the desalination system; however, it decreases the water harvest rate. Long-term experiments should be conducted to draw clearer conclusions. The cost effectiveness and environmental impact of the desalination system also need to be evaluated in future studies.

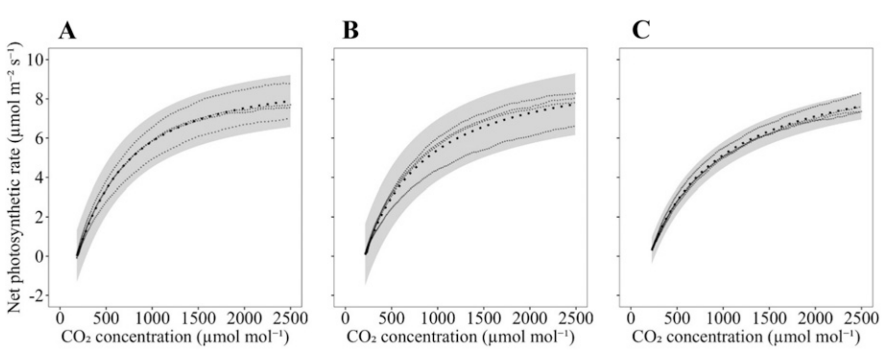

Fig. 7. Net photosynthetic rate of lettuce plants as a function of CO_2 concentration at 0% (A), 10% (B), and 20% (C) of the specified seawater concentration. Plots with fitted curves (dotted lines) and prediction intervals (gray ribbons) are shown (number of samples: 3 to 4).

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