Our water-saving mist cultivation system grows lettuce with 70% less water

Stockholm Junior Water Prize 2024 Entry

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FLORA HUNTERS

JAPAN

(a) Abstract

Water scarcity will become a serious problem due to climate change and population growth. In this research, we have introduced a water-saving mist cultivation system, comprising a sealed container and an ultrasonic mist generator. One of the features of this system is the intermittent supply of nutrient solution in mist form. We confirmed that optimization of water supply frequency enabled operation with about 70% less water, 65% less CO_2 emission, and 84% less nutrients compared to conventional hydroponics without scarifying the yield of lettuce. In addition, we found that the sugar content in tomato could be increased by controlling the watering frequency and time.

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(c) List of abbreviations

DFT: Deep Flow Technique
NFT: Nutrient Film Technique
NH_4-N: Ammonium nitrogen (mg/L)

NO_3-N: Nitrate nitrogen (mg/L)
PO_4-P: Phosphate phosphorus (mg/L)
DO: Dissolved oxygen (mg/L)

(d) Acknowledgements

We would like to express our gratitude to Dr. Gyuyoung YOON from Nagoya City University for his guidance on mist. We would also like to thank the Japanese Society of Plant Physiologists for their instruction. Additionally, we are deeply grateful to Hyponex Japan Ltd. for the information on fertilizers.

(e) Self-Introduction

Shion Akaishi

I am a third-year student in the Environmental system course at Aomori Prefectural Nakui Agricultural High School. In this research project, I was responsible for device fabrication and cultivation experiments. Through this research, I have learned about the fact that the significant amount of usage of freshwater for agricultural purposes. With the knowledge and experiences obtained from this study, I aspire to contribute to the resolution of global water and environmental issues in the future.

Koya Shiratori

I am a third-year student in the Environmental system course at Aomori Prefectural Nakui Agricultural High School. In this research project, I was responsible for mist characterization and water quality analysis in the cultivation experiments. Through this research, I have been able to learn about various issues related to water and food. In the future, I intend to continue my research and contribute to solving global water-related problems.

1. Introduction

Earth is the only planet in the solar system that has rivers and oceans, and about 70% of its surface is covered by liquid water. However, it is known that 97.5% of the water is saltwater, and freshwater accounts for only 2.5%. Moreover, the majority of freshwater is in snow and ice, leaving only 0.01% of usable freshwater [1]. It is estimated that one out of every five people in the world already lacks access to safe water. By 2050, the world's population is projected to exceed 9 billion, resulting in an increased demand for water resources to sustain growing population. Moreover, the impacts of climate change, such as droughts, are becoming more frequent, exacerbating water shortages in arid and semi-arid regions and leading to conflicts over water resources. Surprisingly, approximately 70% of this precious water is used for agricultural purposes [2]. Therefore, it is crucial for us to consider sustainable water management, including the appropriate and responsible use of water resources for agricultural purposes.

In recent years, hydroponic cultivation has been gaining popularity. Its advantages include: approximately 80% less water consumption compared to traditional field cultivation, no soil erosion and degradation, space-saving, faster growth and larger yield, and less vulnerable to the impacts of climate change. As a result, hydroponic cultivation has been introduced in developing countries such as Zambia (Fig.1) [3], and it is predicted that the market will increase by over 30% by 2029 [4]. However, hydroponic cultivation also has its drawbacks such as: high installation cost, complexity of the system, the need for careful management, high energy consumption, and the need for wastewater treatment [5].

We are learning about hydroponic cultivation in a class (Fig.2). However, even though the water usage is relatively low, we still need to constantly circulate the nutrient solution using pumps to supply oxygen, resulting in the consumption of about 7 tons of

Fig.1 Hydroponic cultivation in Zambia [3]

Fig.2 Hydroponic cultivation in our school

water in our hydroponic greenhouse. Therefore, as students studying agriculture, we believe it is our responsibility to come up with innovative solutions and develop new hydroponic cultivation methods that can effectively utilize water resources.

Traditional hydroponic cultivation commonly involves two methods: Deep Flow Technique (DFT), where the roots are submerged in a nutrient solution, and Nutrient Film Technique (NFT), where a nutrient solution flows over the roots [6] (Fig.3). Instead of these traditional methods, the method we have focused on is aeroponics, which has been more recently developed and involves supplying the roots with nutrient solution. This cultivation method is evaluated to have even higher water-saving potential [7], but it has not been widely adopted due to the requirement for advanced technical expertise.

In this study, we have developed a water-saving mist cultivation system. Conventional aeroponic systems utilize air pressure to spray nutrient solution particles with a diameter of around 0.05mm from sprinkler nozzles. However, this method produces a lot of splashes, which can stimulate the roots and cause issues such as pipe

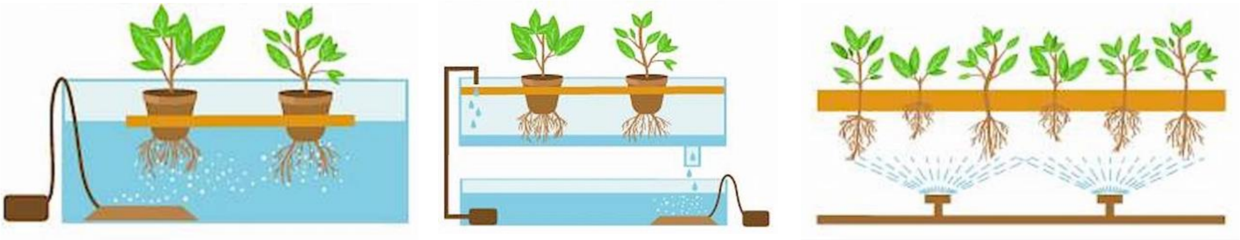


Fig.3 Types of hydroponics: (left) Deep Flow Technique (middle) Nutrient Film Technique (right) Aeroponics

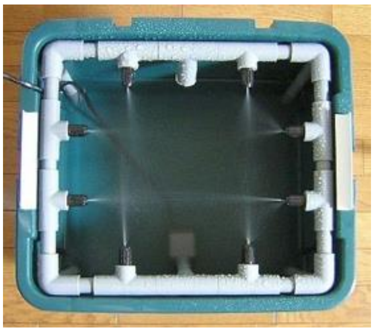
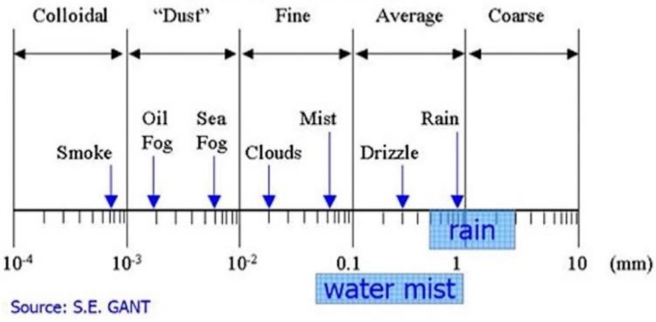


Fig.4 Conventional aeroponics device

Fig.5 Ultrasonic generator device



Source: S.E. GANT

Fig.6 Water drop size

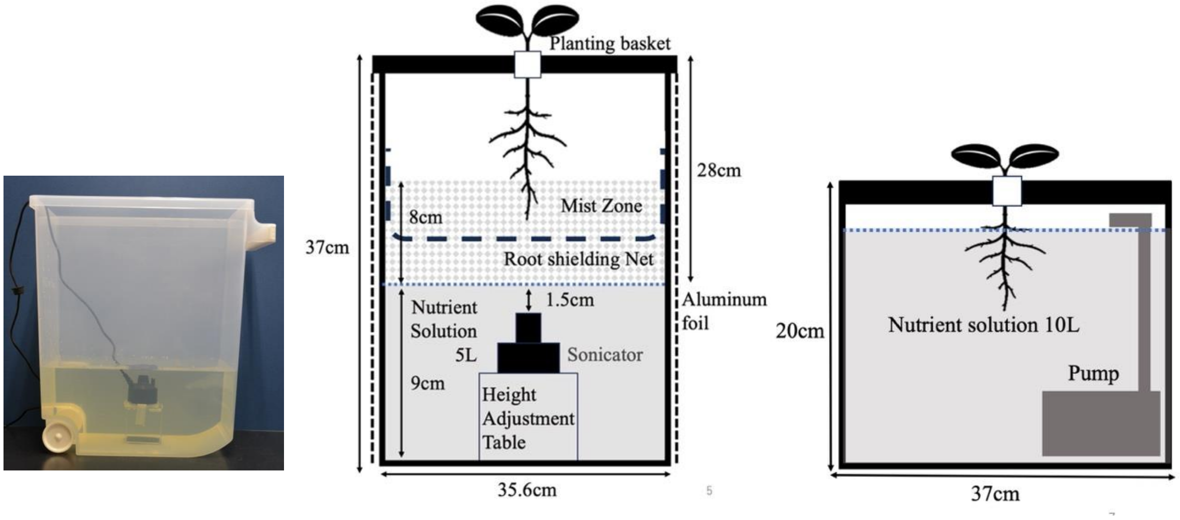
cracks and nozzle clogging due to high water pressure (Fig.4). To address these drawbacks, we constructed our own cultivation device using a small ultrasonic mist generator commonly used in humidifiers (Fig.5). This device operates by vibrating a diaphragm to atomize the nutrient solution, resulting in fewer malfunctions and easy maintenance due to its simple mechanism. Additionally, we believed that generating fine particles with a diameter of around 0.01mm (Fig.6) would reduce stress on the crops, minimizing root stimulation and other stresses [8].

The purpose of this study was to evaluate whether the developed water-saving mist cultivation system could cultivate healthy crops with less amount of water, less CO_2 emission, and less amount of nutrients compared to conventional hydroponics. Notably, our study is unique as there is a lack of research specifically focused on optimal cultivation conditions for grains, making our approach original. Furthermore, we have demonstrated that this new technology has a low environmental impact due to reduced power consumption and fertilizer usage.

2. Materials and methods

2.1 Cultivation system

We constructed a cultivation system using a 10L polyethylene container (35.6cm in length, 22.8cm in width, and 37cm in depth) (Fig.7). The container was sealed to prevent loss of mist that was not absorbed by the crops. The nutrient solution contained 5L of diluted liquid fertilizer (HYPONEX N6.5%-P6%-K19%) with a dilution factor of 1000. A small ultrasonic mist generator (AGPTEC, with a vaporization capacity of 400ml/h and a power usage of 24W) was installed at the bottom of the container. The mist was activated by an ON-OFF timer. Each mist generation lasted for 15 minutes. To prevent the roots from contacting with the nutrient solution directly, a mesh sheet with a pore size of 0.6cm was placed above the mist generator. Additionally, to inhibit algae growth in our system, the system was covered with aluminum foil, as the cultivation was conducted in a greenhouse. As a control, we also fabricated a DFT hydroponic cultivation system with the same scale. The nutrient solution for the DFT system was maintained to be 10L, and continuously circulated using a pump (maximum flow rate of 500L/h, power usage of 17W).



a b

Fig.7 Cultivation system (a: Mist cultivation b:Hydroponic cultivation)

2.2 Mist characterization

To propose a cultivation method utilizing mist, it is important to understand the characteristics of mist. Therefore, we observed the formation and dissipation of the mist zone. Additionally, to investigate the influence of mist on the level of humidity, we measured the humidity in the cultivation container.

2.3 Evaporation test

To evaluate the water-saving performance of our system, we measured the water evaporation rates in four days. For the hydroponic cultivation system and the mist cultivation system, we used the devices shown in Fig.7. The pump in the hydroponic system was ON continuously, while the mist generator operated 24 times a day (for 15 minutes each time). Additionally, we measured the evaporation from a pot containing 3L of Akadama soil with 0.3L of nutrient solution. It is important to mention that no crops were planted to stop transpiration.

2.4 Transpiration test

Transpiration rate could differ between continuous immersion in nutrient solution (hydroponic cultivation) and intermittent spraying of nutrient solution (mist cultivation). Therefore, we performed transpiration tests (Fig.8). For the experiment, we used two lettuce plants in each plot, using a sealed container with a capacity of 7.2L to prevent natural evaporation. The nutrient solution volumes were set at 6L for hydroponic cultivation and 2L for mist cultivation. In hydroponic cultivation, continuous aeration was provided, while in mist cultivation, spraying was performed intermittently (Table 2). The transpiration rates were calculated based on the change in nutrient solution volume after 10 days.

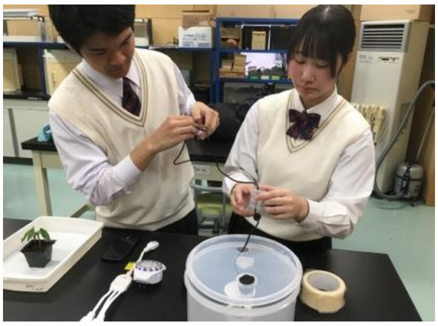


Fig.8 Experimental setup for transpiration tests

Table 2 Experimental conditions for transpiration tests

Type	
Hydroponics	Constantly pump ON
Mist24	Spray 100ml of mist for 15 minutes every 1 hour, 24 times a day.
Mist48	Spray 100ml of mist for 15 minutes every 30 minutes, 48 times a day.

2.5 Cultivation test

The crops selected for the experiment were lettuce *(Lactuca sativa var. crispa*) and kidney beans (*Phaseolus vulgaris L.*). Lettuce is a leafy vegetable widely consumed and originally from China, the Near East, and the Mediterranean region. In this experiment, we specifically chose leaf lettuce because it is susceptible to drought. Kidney beans are legumes native to Central and South America and are consumed worldwide. They are also a valuable source of protein in developing countries. Same as transpiration test, the experiments were performed with 3 conditions: Mist24, which sprayed 100ml of mist every 1 hour for 15 minutes, Mist48, which sprayed mist every 30 minutes, and hydroponic cultivation as a control. For each condition, two devices containing four plants were prepared for lettuce and one plant for kidney beans (Fig.9).

Fig.9 Experimental setup for cultivation tests

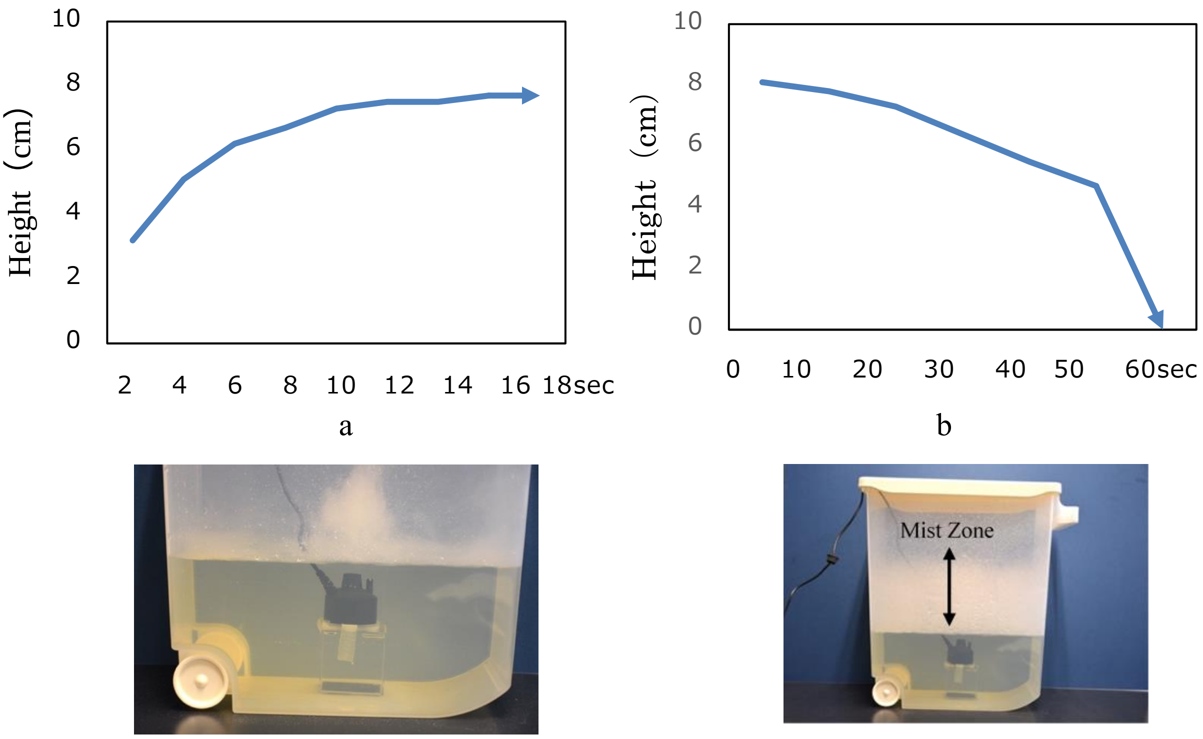
2.6 Analytical methods

The pH was measured using LAQUAtwin-pH-11B (Horiba, Japan). NH_4-N, NO_3-N, PO_4-P were colorimetrically quantified using DPM2 (Kyoritsu Chemical-Check Lab., Japan). The concentration of DO was measured using PDO-519 (FUSO, Japan). Additionally, plant height, leaf number, SPAD (chlorophyll content), and yield were measured as indicators of crops growth.

3 Results and discussion

3.1 Mist characterization

Fig.10 showed that the mist accumulated near the water surface without diffusing in the container. Within approximately 18 seconds, a stable mist zone with a height of 8cm was formed. Although the size of the mist particles was around 10μm, it is larger than water molecules (0.0004μm). Therefore, the mist did not disperse but formed a mist zone with consistent height. After turning off the mist generator, the mist zone gradually descended and it dissipated after 60 seconds. Compared to raindrops, which have a size of approximately 2mm, the mist particles are small. As a result, even after the mist generator was turned off, the mist did not immediately fall but remained suspended for a while. This suggests that the behavior of mist is between droplets and water vapor.



a b

c d

Fig.10 Formation and dissipation of the mist zone
(a: Formation b: Dissipation c: Mist generation d: Formed Mist zone)

Fig.11 shows the changes of humidity in our system over 60 seconds after the generation of the mist. The humidity near the water surface, 5cm above, increased immediately after the mist generation and exceeded 70% after 60 seconds. This can be attributed to the presence of the mist zone. However, the humidity at 28cm above the water surface, outside the mist zone, also reached 70% after 60 seconds. This suggests that a portion of the generated mist evaporated quickly and diffused as water vapor in the container. In this experiment, although the mist itself did not disperse, it transformed into water vapor and increased the humidity inside the container. This high humidity created by the mist can be considered a valuable source of moisture for water-saving cultivation methods.

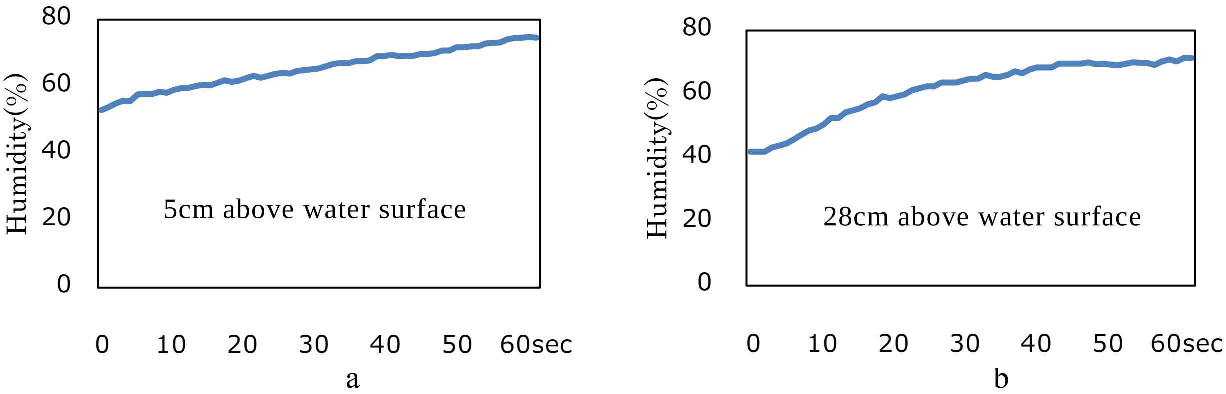


Fig.11 Humidity change over 60 seconds
(a: 5cm above the water surface, b: 28cm above the water surface)

3.2 Evaporation test

To conserve water, it is necessary to reduce unnecessary evaporation from the system. Therefore, the amount of evaporation was measured over a period of 96 hours (Fig.12). The results showed that 60% of water evaporated from the soil, 6.1% from the hydroponics, and only 0.1% of water evaporated from the mist system. This significant difference can be attributed to the degree of sealing of each system. These results demonstrated that water evaporation can be significantly reduced by using mist system.

Moisture is crucial for supporting the life of crops in water-deficient environments,

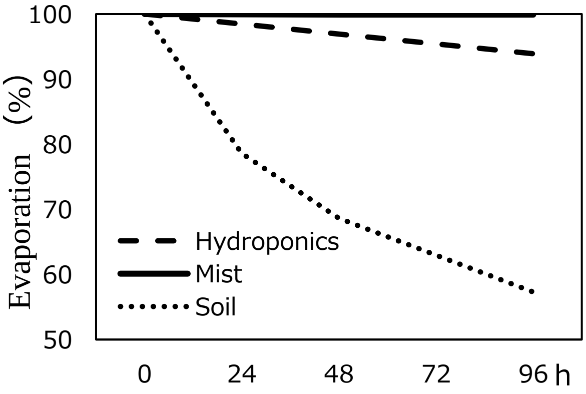


Fig.12 Water evaporation

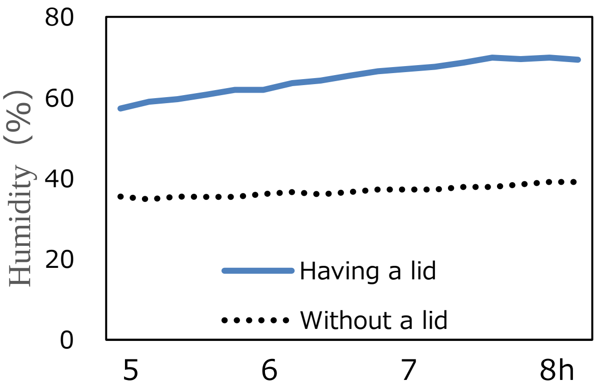


Fig.13 Humidity change during 5-8 hours

and it is essential to maintain humidity within the container. Therefore, the humidity inside the container was measured after stopping the mist generation (Fig.13). The measurement was taken 28cm above the water surface, higher than the mist zone. The results showed that the lid can maintain high humidity for a long time. These results demonstrated the important role of sealed containers in water-saving cultivation.

3.3 Transpiration test

The transpiration test (Fig.13) during lettuce cultivation in hydroponics and mist cultivation systems showed that the transpiration rate in hydroponics was 9.72% (583mL), while only 5.6% (112.5mL) in mist cultivation. This difference can be interpreted that the mist cultivation, which absorbs water only during misting, resulted in reduced water absorption.

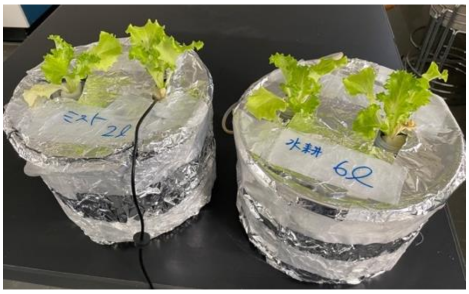


Fig.13 Transpiration test

3.4 Cultivation test

3.4.1 Temperature

The temperature inside the greenhouse reached over 30℃ during sunny daytime hours, but the average remained at 20℃ (Fig.14). This temperature range falls within the suitable growth range for lettuce and green beans.

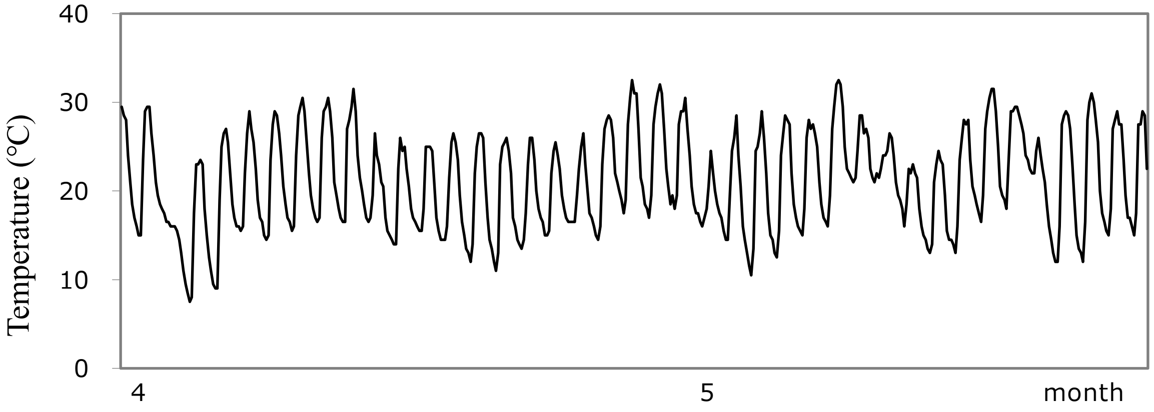


Fig.14 Temperature changes during cultivation experiments

3.4.2 Cultivation

Fig.15 shows the growth of lettuce. The plant height (and number of leaves, data not shown) was similar for the control hydroponic cultivation and Mist48, and they grew well. On the other hand, Mist24 showed shorter plant height (and smaller number of leaf count, data not shown). Lettuce leaves are thin and susceptible to drying, so it was expected that the plants experienced water shortage in Mist24. Additionally, in mist cultivation, the SPAD value, which indicates chlorophyll content, was slightly higher. The reason of this result is unknown, but it did not have any significant impact on crop growth.

Fig.16 represents the growth of green beans. In the case of green beans, there was no significant difference in plant height and SPAD values between Mist24 and the control hydroponic cultivation. Unlike lettuce, green beans have thick stems and leaves, allowing them to retain a significant amount of water within their plant bodies. Therefore, they were less affected by water-deficient environments.

Fig.17 shows pictures of roots after 25 days cultivation. In both lettuce and green beans, the Mist48 exhibited fine root hairs and longer roots that were not present in the hydroponic control group. These are called aerial roots, specialized roots that absorb moisture from the air, and are formed by crops to adapt to water-deficient environments. During the dry period between misting events, it is believed that the crops absorb

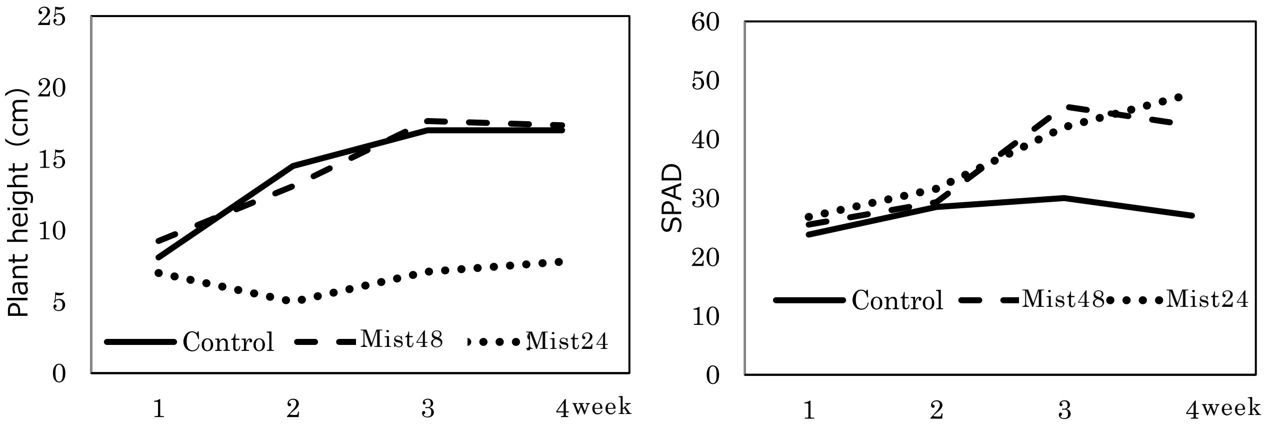


Fig.15 Growth of lettuce

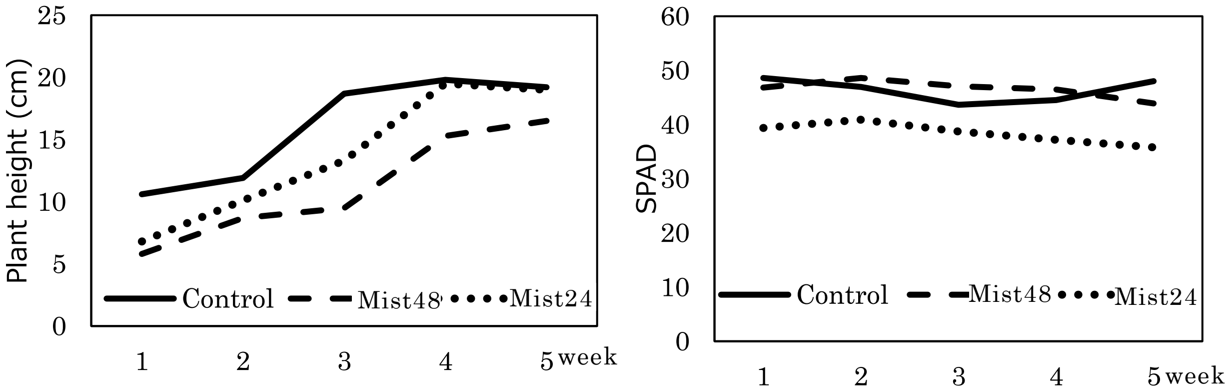


Fig.16 Growth of green beans

Fig.17 Root of (a) lettuce and (b) green beans (left: hydroponics right: Mist48)

moisture from the humid environment in the enclosed container through these aerial roots. Thus, although the frequency of misting may vary depending on the crop, it has been found that mist cultivation is possible for many crops with appropriate water management.

3.4.3 Yield

The yield of lettuce after 4 weeks cultivation is shown in Fig.18. The results showed no significant difference between the control hydroponic cultivation and Mist48. However, the Mist24 group had lower overall and edible weights (stems and leaves). However, the difference in polyphenol content was not significant. Polyphenols are plant pigments synthesized as a response to stress and can contribute to bitterness. There were concerns that mist cultivation could increase polyphenol levels and negatively affect the taste. However, the comparable levels of polyphenol content suggested that the stress imposed by water-saving environment was not significant.

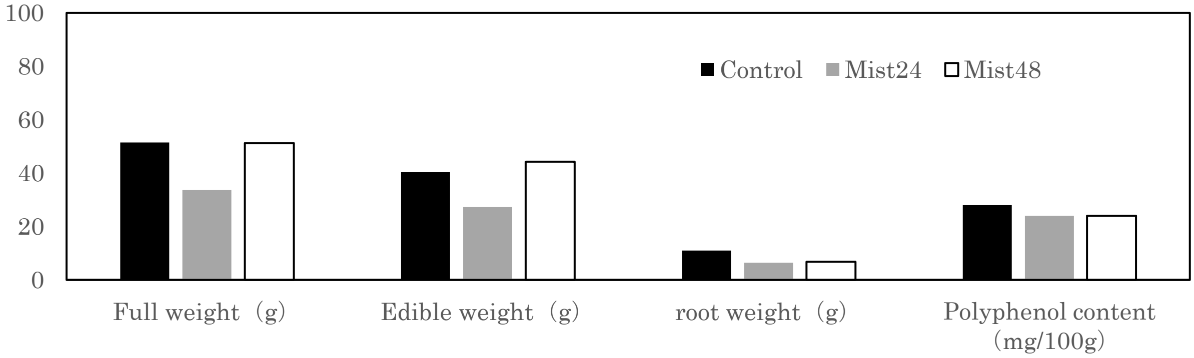


Fig.18 Comparison of lettuce yields

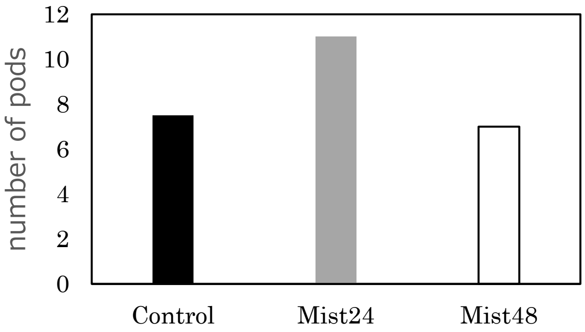


Fig. 19 Pods of green beans after 63 days cultivation

Fig.19 represents the number of pods of green beans after 63 days cultivation. There was no significant difference between the control hydroponic and mist cultivation. Green beans have thick stems and can store a significant amount of water, which makes them less susceptible to water-saving environments. The number of pods directly affects the yield of edible beans. From these results, it can be concluded that a comparable yield as control hydroponics can be obtained by mist cultivation.

3.4.4 Nutrient solutions

pH and the concentration of dissolved oxygen (DO) were measured during the cultivation. The results showed that the pH remained near neutral (~pH6.0). Therefore, it can be concluded that mist cultivation provides a favorable environment for healthy growth. Additionally, it was observed that the DO level in the control hydroponics (7~8mg/L) was higher than that in mist cultivation (6~7mg/L). This is because in control hydroponic cultivation the nutrient solution is continuously agitated by a pump to maintain DO concentration. However, it is important to mention that in mist cultivation, in which the roots are exposed to the air, there is no need to obtain oxygen from the nutrient solution like hydroponics. Therefore, it is believed that the plants can absorb enough amount of oxygen from the air, without relying on the DO level of the nutrient solution.

We keep using lettuce as an example, and Fig.20 represents the amount of NH_4-N, NO_3-N, and PO_4-P absorbed by lettuce during the 25 days cultivation. The results revealed that the control hydroponics absorbed a significant amount of nutrients. Most of the absorption occurred within the first week after planting. On the other hand, the nutrient absorption in mist cultivation was lower. This is because the lettuce can only absorb nutrients when it is being misted. However, despite the lower nutrient absorption, there was no significant difference in yield (Figs.18 and 19). Therefore, it indicated that the control hydroponics accumulated the absorbed nutrients in the stems and leaves. Excessive nitrogen in the form of nitrate nitrogen can have detrimental effects on plant health. Therefore, it can be inferred that, mist cultivation can help to mitigate health risks and contribute to save fertilizers, which have been recently increasingly expensive.

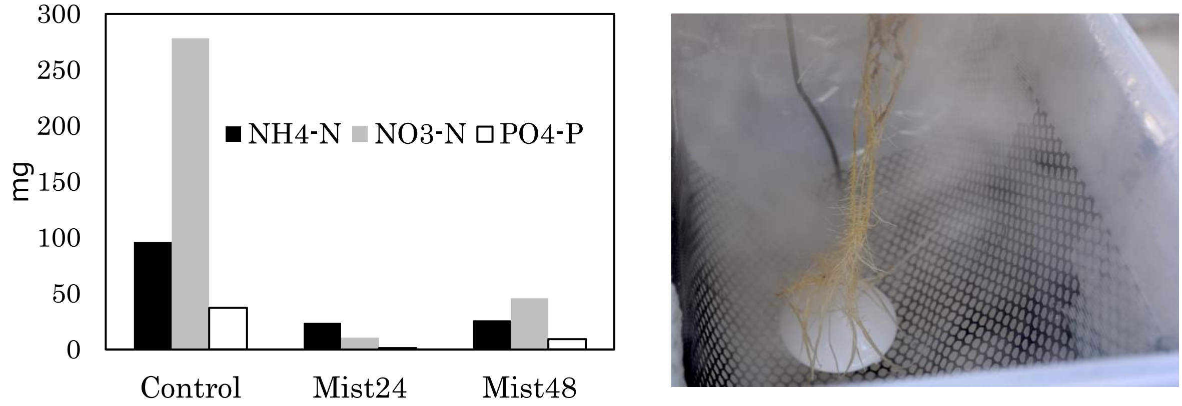


Fig.20 The amount of absorbed nutrients during lettuce cultivation

3.4.5 Environmental significance

3.4.5.1 Water usage

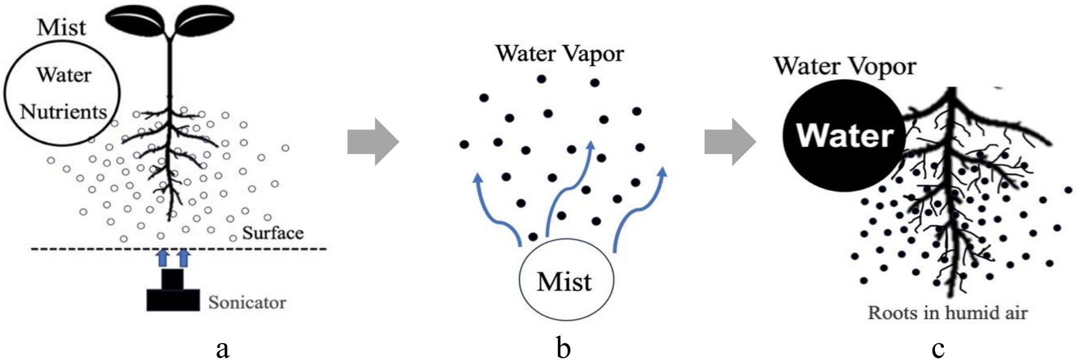
Table 3 compares the water-saving performance of mist cultivation for lettuce. The results showed that Mist24 and Mist48 both exhibited a high water-saving rate of approximately 70% in total. This achievement can be attributed to the adoption of small ultrasonic generators that can operate with a small amount of water, the development of enclosed systems that suppress water evaporation, and the reduction of water transpiration by limiting the crop's water absorption through intermittent mist generation. Fig.21 illustrates the mechanism which allows crops to grow in an environment where water is provided intermittently. When mist is generated, crops absorb the water from the mist, which supports their growth. Some of the mist instantly evaporates and diffuses into the container. However, the mist stops after 15 minutes. At this point, crops are believed to survive by absorbing water vapor from the container using their aerial roots until the next mist generation. Thus, mist cultivation is based on the combination of human water-saving efforts and the special capabilities of crops to absorb water from the humid atmosphere.

3.4.5.2 CO_2 emission and nutrients

The calculation of annual carbon dioxide emissions based on power consumption

Table 3　Comparison of water usage during lettuce cultivation

	Initial required water	Evaporation and transpiration	Total water usage	Reduction
Hydroponics	10L	3L	13L	-
Mist24	3L	0.5L	3.5L	73.1%
Mist48	3L	1L	4L	69.2%



a　b　c

Fig.21 Mechanism of crop growth under water-saving environment

(a: pump ON　b: water evaporation from mist　c: pump OFF)

and operating time indicated that Mist48 can reduce emissions by approximately 30% compared to hydroponic cultivation, while Mist24 can achieve a reduction of approximately 65%. This is due to the intermittent operation of low-power devices in mist cultivation. In addition, the calculation of the nutrient absorption by lettuce during 25 days cultivation showed that the absorption of nutrient was significantly lower for Mist48 compared to control hydroponics: 72.9% lower for NH_4-N, 83.5% for NO_3-N, and 75.1% for PO_4-P.

4. Future perspectives

Currently, NASA's Artemis program, a lunar exploration initiative, is progressing [9]. The program aims to send humans to the Moon by 2025. It has evolved into an international endeavor with the participation of 40 countries including Sweden. While numerous difficulties need to be overcome, one of them is water. Food production is essential for human habitation on the Moon, but sourcing water from Earth is estimated to cost as much as 150 billion US$ per liter. Our water-saving mist cultivation system, which effectively utilizes limited water resources multiple times, holds potential for application in food production in space. We believe in the potential of our technology to contribute to the advancement of humanity and continue our research on water conservation to make a global impact.

In addition to its water-saving capability, we have shown that our mist cultivation can also improve the quality of crops. Although we are still in the middle of the experiment and need to perform more experiment, we would like to introduce the results we have obtained so far. In this cultivation experiment, we chose tomato as a target crop. Tomatoes with a sugar content of 8 degrees or higher are traded at higher prices in Japan [10]. The key to achieving high sugar content is water restriction. However, it is challenging to maintain constant water restriction in hydroponic cultivation, where the roots are constantly immersed in nutrient solution. Therefore, we performed experiments with careful control of watering frequency and timing (Table 4). As a result, we found that by spraying the mist irregularly: once every hour from 8 AM to 4 PM and twice at 9 PM and 2 AM (Mist11-irregular), we were able to produce tomatoes with a sugar content (brix) of 11.5 degrees or higher (Fig.22). This is probably because restricting water uptake during the night helped to minimize sugar dilution. This cultivation method, which has not been seen before, demonstrates the effectiveness of mist cultivation as a viable technique for commercial cultivation.

Fig.22 Tomatoes grown by mist cultivation

Table 4 Influence of watering frequency and time on sugar content of tomato

	Watering frequency and time	Brix (%)	Weight(g)
Hydroponics	Roots are constantly immersed in nutrient solution	7.6	54.0
Mist11-regular	100ml each time for 15 minutes, 11 times a day 0,3,5,7,9,11,13,15,17,19,21 o’clock	7.8	49.8
Mist11-irregular	100ml each time for 15 minutes, 11 times a day 2,8,9,10,11,12,13,14,15,16,21 o’clock	11.5	49.0

5 Conclusions

We have developed a new water-saving mist cultivation system. With this system, we were able to reduce the amount of required water by about 70% compared to traditional hydroponic cultivation. The CO_2 emission and nutrient consumption also significantly reduced by introducing our system. We are confident that our system, which has been developed from the perspective of efficient water utilization, along with the cultivation methods utilizing the characteristics of mist and plants, can make significant contributions to the effective use of precious water resources.

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