High Quality Agricultural Production Support System by Smart Sand Cultivation Device "New Sandponics"

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New Sandponics (NSP) is a unique cultivation device that uses sand as the primary medium, and additionally employs a floor irrigation method in the early Sandponics. Using only 10% of the sand medium volume used in the early Sandponics, NSP reduces the device weight and maintenance costs. The floor irrigation method has enabled us to control water and fertilizer supply depending on the growth phase of crops for high yields and quality. This paper reports on our efforts in increasing the yield of tomatoes by using a new medium with air-rich structures and also presents our attempts at IoT-based agricultural production using Sandponics.

Keywords: Hydroponic culture, sand culture, floor irrigation

1. Introduction

The agricultural production support system business that we have been carrying out since the 1970s originates from the "industrialization of agriculture" initiative promoted by Mr. Kazue Kitagawa, Chairman of Sumitomo Electric Industries, Ltd. at the time. The combination of agriculture and information society[1] proposed in those days has become real now thanks to the information technology that has developed dramatically in the 21st century, proving that the initiative was promising. Under the circumstances of the global food shortage with population growth and the agricultural labor power shortage with population aging, the realization of the initiative has become increasingly important in recent years.

Our sand culture system "Sandponics" has been marketed since 1977 as a dripping culture system mainly used for growing melons and vegetables in greenhouses. It is highly regarded for (1) using sand that has stable physical properties, (2) introducing a controlled culture method that generates less drainage, and (3) enabling continuous culture.[2] Since 2013, we have been working to further improve the system efficiency, and developed "New Sandponics" (NSP) [3], adopting floor irrigation. The new system is under demonstration test of tomato cultivation (Fig. 1).

This paper describes the features of NSP with an example of increasing tomato yields by further refining the features. It also introduces a comprehensive culture support system that realizes stable productivity in agriculture by combining culture with NSP, which is superior in rhizosphere control, monitoring technology and data analysis techniques.

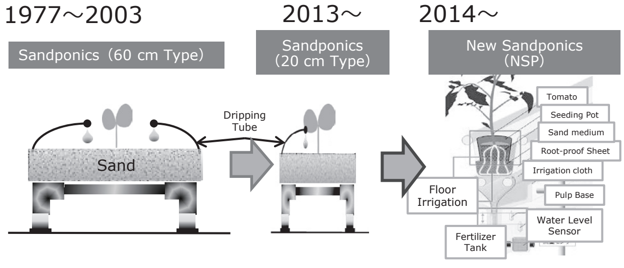


Fig. 1. Development of Sandponics Devices

2. Principle of Floor Irrigation

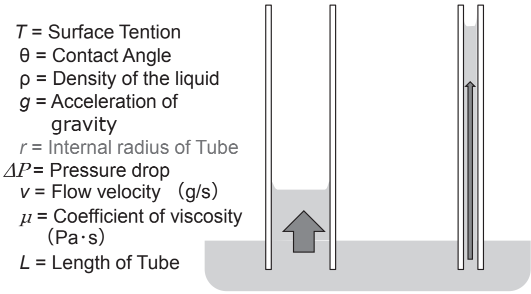
NSP is a liquid fertilizer cultivator that consists of a small amount of sand media with a liquid fertilizer tank at the bottom. It is based on floor irrigation, which supplies fertilizer from the tank using capillary action of an irrigation cloth. (Rightmost in Fig. 1)

Capillary action is a phenomenon in which, when one end of a thin tube (capillary) is inserted in water, the water rises inside the tube against gravity as shown in Fig. 2. The height of the water column is inversely proportional to the tube diameter as shown by Eq. 1 in Fig. 2.

Capillary conductivity is an important characteristic of water movement for the materials for floor irrigation. Its inverse corresponds to permeation resistance to water that passes through a capillary. The permeation resistance of a capillary increases inversely proportional to the tube diameter raised to the 4th power as indicated by Eq. 2 in Fig. 2 (rearranged Poiseuille's equation).

It follows that the thinner a capillary is, the higher the water column rises but it is difficult that the water move up sharply.

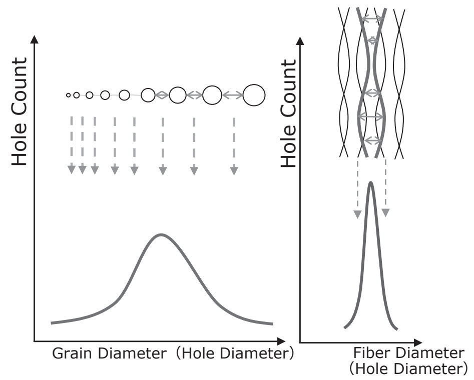
In the floor irrigation system, the gaps and spaces inside the materials of the main components, and the irrigation cloth and media serve as capillaries for sucking up water. For example, the irrigation cloth contains fibers such as nonwoven fabrics and rock wool, in which the gaps between fibers act as capillaries. In the case of granular materials such as sand and cocopeat, the spaces between grains serve as capillaries (with the distances between grains corresponding to pore sizes). For manufactured products such as nonwoven fabrics, which are made by compressing fibers with almost identical diameters, highly



Hole Radius	Large	Small
Pumping Height Equation 1: $h = \frac{2T\cos\theta}{\rho g r}$	Low	High
Permeation Resistance (Moving speed of water) Equation 2: $R = \frac{\Delta P}{v} = \frac{\mu L}{2\rho\pi r^4}$	Low (Fast)	High (Slow)

Fig.2. Relationship between Capillary Action and Irrigation Characteristics

uniform spaces are created. (Right in Fig. 3) In contrast, natural materials including sand and soil generally have broad diameter distributions reflecting the variations in grain diameters. (Left in Fig. 3) Therefore, it is generally believed that the description by treating sand and soil, that have complicated gap structures, as a set of capillaries, has its limits.(4) However, this paper uses this description for gaps and spaces in the sand media for the sake of simplicity.



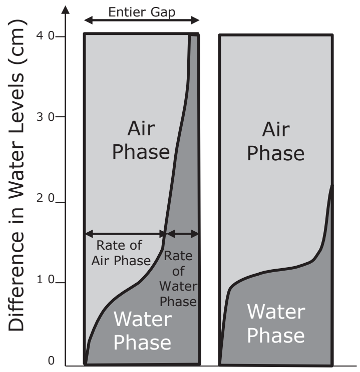
Material	Sand and Soil	Nonwoven fabric
Hole Diameter Distribution	Wide	Narrow

Fig.3. Irrigation Materials and Tube Diameter Distributions

The capillary diameter distribution of each material represents the sizes of capillaries that form the materials. It is the most basic characteristic to determine three important properties of floor irrigation: (1) Pumping capacity; (2) Ratio between the air and water phases in the gap (the ratio varies depending on the difference in water level from the bottom water tank); and (3) Irrigation speed.

Figure 4 describes water content at different water levels from the bottom tank for the typical materials used in the floor irrigation of NSP. The chart indicates the ratio between the air and water phases in the space at each water level (= pumping height).(5)

It may be easy to understand these characteristic curves by considering the columns of capillaries that form each material arranged according to the size with the largest one on the left (Fig. 5). As described in Fig. 1, thick capillaries have lower pumping heights, and the spaces above them are filled with air. Therefore, the higher the difference in water levels is, the greater the rate of air phase reaches.



Material	Sand medium	Nonwoven fabric, Root-proof sheet
Capillary Diameter	Small to medium (Wide distribution)	Relatively large (Narrow distribution)
Pumping Capacity	High	Medium
Irrigation Speed	Slow	Rather Fast

Fig.4. Ratios of the Air and Water Phases in the Irrigation Material for NSP

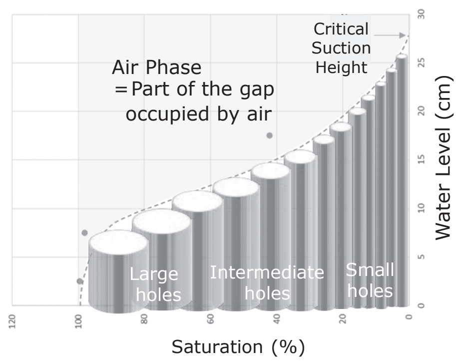


Fig.5. Capillary Diameter Distribution and Ratios of the Air and Water Phases

Considering the irrigation performance of these characteristics based on the principle of capillary action as discussed at the beginning, the sand used as the media for NSP contains many small gaps, sucking up water to high levels in the media layer. However, the moving speed of water is lower than that of the water-permeable root-proof sheet described below. On the other hand, the irrigation cloth and water-permeable root-proof sheet do not suck up water as high as sand, but they are superior in water transfer performance. Therefore, it is possible to provide a moisture environment suitable for growing plants by combining these materials with different moisture characteristics. The details of the combination are described in the next chapter.

3. Features of NSP

NSP is designed on the principle of floor irrigation as described before. It has distinctive features in its structure as listed below (Fig. 6).

(1) Media with a small amount of sand having high pumping performance;
(2) A moisture-permeable root-proof sheet that prevents roots from growing downward;
(3) An irrigation cloth made of a nonwoven fabric that is superior in water transfer;
(4) A bottom water tank with its water level controlled

In addition, as another unique property that is not seen in general, floor irrigation hydroponic cultivators; and

(5) Suspension of the nonwoven fabric so that the lower part of the medium (below the sand media and the lower part of the irrigation cloth in Fig. 6) is in contact with air.

With these structural features, NSP has the following advantages in culture.

(1) With the medium lighter than the conventional sand culture system, it is easy to install and maintain;
(2) Little waste is generated after cultivation. (Roots can be easily removed after production.);
(3) It is possible to control sugar content easily and reliably by constantly applying stable moisture stress with the difference in water levels. (Roots are blocked with the water-permeable root-proof sheets and the water level is controlled using a water tank with a constant water level.);
(4) Fast water supply keeping pace with the water absorption speed of a plant; and
(5) Sufficient oxygen supply to the liquid fertilizer and media

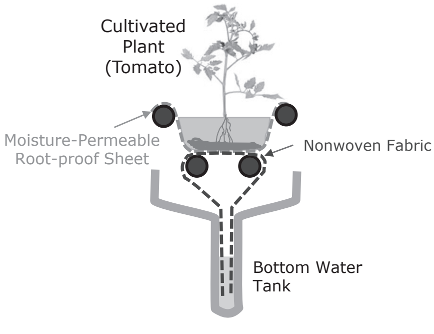


Fig. 6. Schematic Structure of NSP

Compared to hydroponic culture, the benefits of NSP culture result in vigorous expansion of roots and healthy growth of a plant, thereby enabling high-quality and large-quantity harvests. The next chapter describes these advantages by showing an example of tomato cultivation using NSP.

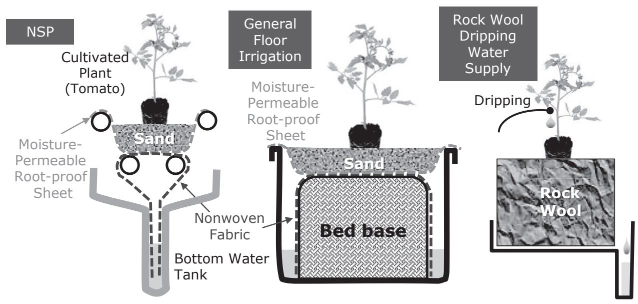
4. Greenhouse Cultivation of Tomatoes Using NSP

4-1 Experiment for comparison with typical hydroponic culture

To compare the performance of NSP with that of other methods, we cultivated tomatoes using NSP and two typical liquid fertilizer culture methods: (1) Floor irrigation sand culture using an irrigation cloth under the soil bed (hereafter, referred to as "soil bed floor irrigation sand culture") and (2) Dripping culture using a rock wool medium.

Tomato seedlings with five fully extended leaves planted in 5 cm-pots with peat moss seedbed from CF Momotaro York were planted in pots with holes at the bottom, then each group of 156 seedlings were planted at intervals of 15 cm directly on the media. The schematic structure of each cultivator, the amount of the media and bottom area, and the irrigation method are shown in Fig. 7.

Seedlings were cultured from May 27 to early October 2016 at Building 1 of the plant factory[6] on Chiba University's Kashiwa-no-ha Campus with 7-stage pinching. The liquid fertilizer was prepared by OAT Greenhouse Fertilizer SA and its concentration was controlled to 0.8-1.0 mS/cm (early) and 1.2 mS/cm (later). Since it was conducted through summer, the environment inside the greenhouse was controlled. During the day, fine-mist cooling was performed at a saturation deficit*1 of 6-8 g/m^3, and at night, the environment was heated up to 25°C with a heat pump. The yields are shown in Table 1.



	NSP	Floor Irrigation on Bed base	Rock Wool Dripping Water Supply
Amount of Medium	400 cm^3 / Seeding	640 cm^3 / Seeding	2400 cm^3 / Seeding
Bottom Area Medium	75 cm^3 / Seeding	150 cm^3 / Seeding	300 cm^3 / Seeding
Water Supply Method	Control by the gap of Medium bottom and Tank water level (over 6 cm :Start, under 5 cm :Stop)		Control by Time schedule (80 cc / seeding every 30 min. during Daytime)

Fig. 7. Structure and Water Supply Method of Each Cultivator

Table 1. Result of Cultivation with NSP, Floor Irrigation, and Rock Wool Dripping

Cultivation Method	NSP	Floor Irrigation on Bed base	Rock Wool Dripping Water Supply
Liquid Fertilizer Consumption	0.3~1.0 L / Seeding・day		1.5 L / Seeding・day
Yield	7.5 ton / 10 a	6.2 ton / 10 a	10.0 ton / 10 a
Average Suger Content	Stable at 6-lower	5 at initial and exceeding 7 later	Stable at 4 to 5
Root Condition	White and Sound	Browned with root decay	White and sound

The culture with the highest yield was obtained by the dripping irrigation culture using a rock wool media. The two-floor irrigation culture recorded high sugar content. The NSP and rock wool cultures provided yields with stable sugar content and fruit weights. The overhauling inspection after cultivation indicated a white root mat*2 formed at the bottom of the medium.

In contrast, the soil bed floor irrigation culture had a reduction in plant vitality in the latter half of cultivation with a surge in sugar content due to a decrease in the average fruit weight. The examination after cultivation revealed the concentration of roots on the side of the medium. The root expansion stopped on the soil bed at the bottom and some roots were browned or decayed.[7]

Although yields were suppressed, NSP enabled high-sugar content culture with much less medium and less liquid fertilizer compared to the other typical cultures.

4-2 Improvements in root distribution of NSP

Unlike dripping irrigation in which water flows down through the medium, the floor irrigation adopted by NSP has a water distribution with more water at deeper levels in the medium. Therefore, the roots have a strong tendency to grow vertically downward. After growing through the medium, its advancement is hindered by the root-proof sheet. However, as the growth above the ground increases, the roots seek water downwards, resulting in an increase in the thickness of the root mat above the root-proof sheet.

As mentioned earlier, NSP enables cultivation with less medium than other cultivation methods. However, since the bottom area of the medium is smaller, a thicker root mat is formed. (Right in Fig. 8)

The roots in upper layers of the root mat are likely to have difficulties in absorbing liquid fertilizer compared to those in lower layers. This can hinder the growth of a plant, and in some cases, degrade the activity of the roots.

Fig. 8. Medium after NSP Cultivation (Left: Cross-section; Right: Bottom)

A medium with a laminated structure shown in Fig. 9 has been invented to allow root mats, which are specific to floor irrigation, to be formed in layers, solving the problems of enlargement and malfunction of roof mats while maintaining the features of NSP culture, and thus obtaining high sugar content with small media and floor irrigation.

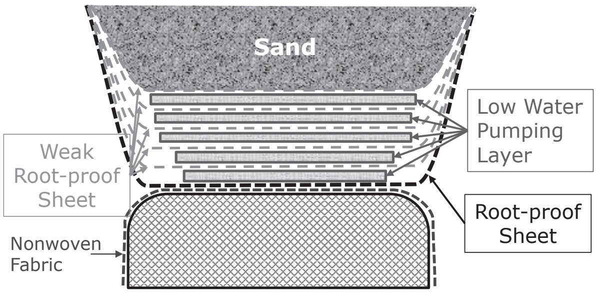


Fig. 9. Lamination of the Medium

The effects of the layered structure were examined with tomatoes. With the target of comparison being the soil bed floor irrigation culture as shown in Fig. 7, a five-layer laminated structure illustrated in Fig. 9 was created in the lower half (approximately 1.5 cm thick) of the 3 cm-thick sand media, using the following materials.

Weak root-proof sheet:
RG-W Water Permeable Root-Proof Sheet from Bell Kaihatsu
Low Water Pumping Layer:
(1) SR250 Aquabell Nonwoven Fabric from Bell Kaihatsu
(2) Towada sand layer (above SR250)
Root-Proof Sheet:
Water Permeable Root-Proof Sheet from Bell Kaihatsu (Special order)

In the experiment, weak root-proof sheets and low water pumping layers are arranged repeatedly to form a five-layer structure with the bottom layer being a root-proof sheet (Fig. 9).

The RG-W weak root-proof sheet blocks roots but some tomato roots penetrate the sheet and expand into the lower layers. The SR250 low water pumping layer is an unwoven fabric with a thickness of approximately 250 µm. The pumping height described by the manufacturer is 4 cm. Therefore, when the difference in water levels between the medium and water tank is 5 to 6 cm, many gaps cannot suck water, which creates an air phase.

Towada Sand is gravel with a grain diameter of up to several mm and having voids inside. This sand is expected to increase the amount of air layers.

The experiment of tomato cultivation was conducted under the same conditions with that in the previous chapter, except that the cultivation period was between June 30 and early November 2016. The result is indicated in Table 2.

Table 2. Result of Cultivation Using NSP with Laminated Structure

Cultivation Method	General Floor Irrigation	Laminated Structure (1)	Laminated Structure (2)
Medium Structure	1.5 cm thick Sand 2101	1.5 cm thick sand RG-W/SR250 × 5 layers 2101	1.5 cm thick sand Same as left + Towada Sand × 5 layers 2101
Yield	5.5 ton / 10 a	7.4 ton / 10 a	8.1 ton / 10 a
Average Sugar Content	5 at initial and exceeding 7 later	Stable at 5-higher	Stable at 5-higher
Root Condition	Browned with root decay	White and Sound	

The laminated structure cultivation provided a greater yield because the browning of roots was suppressed compared to the floor irrigation in the comparison experiment section.

5. Consideration of Ideal Floor Irrigation Culture

In cultivation with a laminated medium, the overhauling inspection of the medium revealed the expansion of roots on the upper surface of the weak root-proof sheet in five layers, which indicates lamination of root mats that was not seen in the floor irrigation culture (Fig. 10).

As described earlier, the floor irrigation is superior in being able to attain a high quality of yields such as high sugar content by restricting water. However, this method has the risk of limiting the expansion and distribution of roots, which support plant vitality.

This tendency is particularly noticeable with NSP that uses only a small amount of medium. However, considering oxygen supply to roots, it has been revealed that a small amount of medium has advantages.

The test results suggest that oxygen supply is important for the growth and maintenance of roots in floor irrigation culture using sand, as well as the supply of liquid fertilizer. It is assumed that NSP has suppressed the reduction in root activities as it uses the water permeable root-proof sheets and irrigation cloths hanged like a hammock to create spaces just below the bottom of the medium, in which the root mat grows and oxygen is supplied to the medium.

The lamination test indicated root expansion through a weak root-proof sheet, which restricts vertical advancement of roots. Similarly, the observation also indicated that there is an air phase under a concentration of roots.

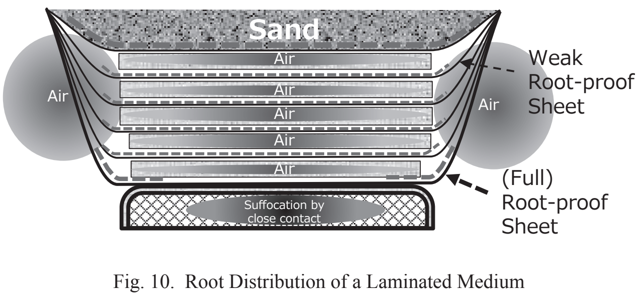


Fig. 10. Root Distribution of a Laminated Medium (Indicated with broken line)

Summarizing the results and consideration, an ideal form of floor irrigation consists of (1) liquid nutrient supply with the distinctively high pumping performance of sand medium, and (2) fast supply of liquid fertilizer and oxygen from the liquid fertilizer tank to the bottom of the medium. NSP has embodied these features (Fig. 11).

Lastly, we introduce a cultivation support system using Sandponics we are currently developing.

NSP is a floor irrigation cultivator that is controlled by the difference in water levels from the sand medium. NSP enables the measurement and management of the amount of absorbed liquid fertilizer in real-time, which makes it the only cultivator that can offer controllable environmental conditions using sunlight.

We are currently developing an agriculture support system that achieves vegetable yields with the highest quality in the maximum quantity by using the advantages of NSP.

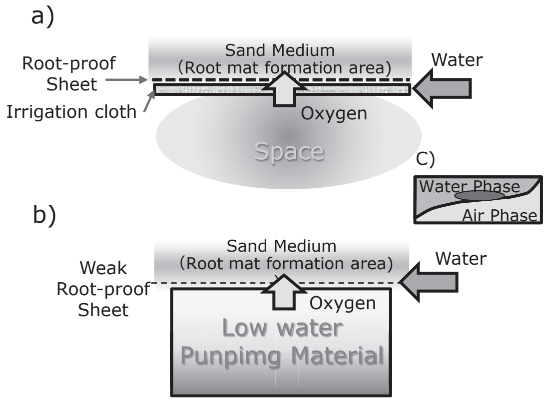


Fig. 11. Example of an Ideal Floor Irrigation Cultivation Method (schematic)
a) Bottom of NSP; b) Layers of the laminated structure;
c) Common environmental states

6. Cultivation Support System

Specifically, it has a form of an information processing system illustrated in Fig. 12. This system provides cultivation recipes for the greatest yields based on the quantity data on plant cultivation obtained from the site.

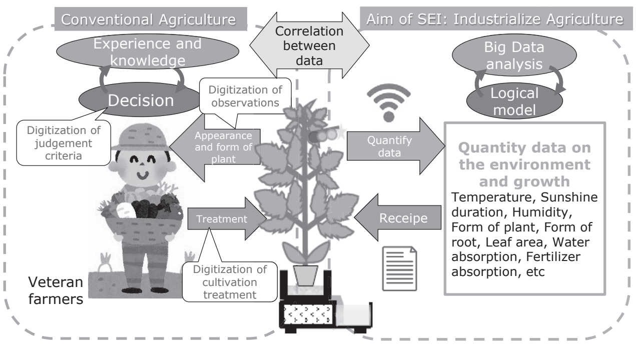


Fig. 12. Agricultural Production Support System Utilizing IoT

We are planning to store data on the facilities, environments, and preparation works for tomato cultivation in Chiba and Osaka into a central server and analyze the data to create cultivation recipes and examine the results.

Although in a specific environment on a limited scale, the analysis has indicated that (1) sugar content was increased by adjusting the concentration of liquid fertilizer, (2) yields were increased by controlling pH of the liquid fertilizer, and (3) yields were increased by changing the irrigation system. In the case of tomato cultivation in a greenhouse of a plant factory in Chiba, the conditions for achieving an annual target (Fig. 13) of a sugar content of 6 or higher and a yield of 22.5 t/10 a has been clarified (Table 3).

Table 3. Example of Cultivating Tomatoes According to the Recipe

Cultivation Section	Target Value	Comparison	Fertilizer Adjustment	pH adjustment	Auxiliary Dripping
Cultivation Recipe		Rock Wool dripping cultivation	1.2 times Concentration of Fertilizer	pH of Well water 5 to 6.5	8% dripping
Summer Yield (ton / 10 a)	10	11.1	9.8	7.5	10.5
Annual Yield (accumulated, ton / 10 a)	22.5	23.6	22.3	20.0	23
Average Sugar Content	6 or higher	5	5.8	6.6	6.2

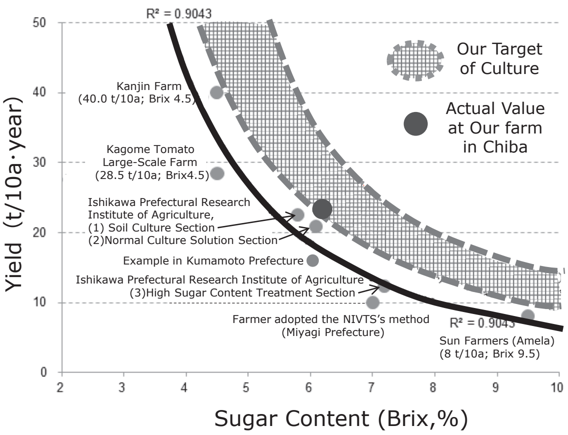


Fig. 13. General Tomato Culture and Culture Target/Actual Value(8)

We intend to extend the cultivation media to establish an agriculture support system that responds to various environments, and are aiming to realize a cultivation monitoring system that further promotes the accumulation of know-how within several years.

7. Conclusion

NSP is a new hydroponic cultivator focusing on stable control of the growth of rhizosphere. It offers superior maintainability and stable yields with high quality and large quantity by utilizing (1) a small amount of sand medium, (2) irrigation cloths with an excellent response to the transfer of liquid nutrients, and (3) a large air phase structure that promotes the respiration of roots.

The roots of a plant are sometimes compared to the intestines of a human. Similar to keeping the intestinal environment in good condition is the basis for maintaining good health, the technology for controlling the rhizosphere environment is definitely an important factor for supporting the health and growth of a plant to have the greatest yields.

Our agricultural business starts from seeking the form of agriculture in an information society, and reviews the orientation of the industry from the viewpoint of technology for stable production of industrial products we have developed in our core businesses under the slogan of "industrializing agriculture."

Based on Sandponics, we will continue our efforts for the stabilization of agricultural production by visualizing and quantifying cultivation data in terms of industrial production and by introducing IoT technology for controlling cultivation.

8. Acknowledgments

We are grateful to Dr. Akimasa Nakano of the National Agriculture and Food Research Organization (NARO) for providing consultation and advice.

Technical Terms

*1 Saturation deficit: An index representing the easiness of drying of an environment. It is a physical quantity (g/m^3) that indicates the amount of water vapor, and shown by the weight of water to be accepted by $1m^3$ of air.
It can be obtained by calculating the amount of saturated vapor x (100 – humidity) / 100.

*2 Root mat: Roots or the state of roots laminated in the form of a mat. When the downward growth of roots seeking water below is stopped by a root-proof sheet, the roots continue to grow on the upper surface of the sheet laminating each other to form a root mat.

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