Application of automatic system for water stress treatment to produce high soluble solids tomato (Solanum lycopersicum Mill. cv Rinka 409)

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Abstract. The objectives of this study were to confirm the application of automatic system for detecting the water stress and the compatibility of the water stress treatment system for producing high soluble solids tomato fruits in high technology greenhouse. The tomato variety used, “Rinka 409”, was grown hydroponically with a high-wire system in high technology greenhouse in Faculty of Agriculture, Ehime University, Japan. The greenhouse has a full controlling system (temperature, relative humidity, carbon dioxide, and light intensity) to support the seasonal change and was adjusted to the real-time condition. Water stress condition of the tomato plant in the high technology greenhouse was detected by measuring the water content in the rockwool slab and by using visual monitoring system. The result showed that the automatically nutrient supplying system using visual monitoring system based on speaking plant approach technology could be used for the detection of water stress in the tomato plant. Using this system, water stress tomato cultivation was detected and the high soluble solids tomato fruits could be produced continuously to fulfill consumer expectation.

1. Introduction
Tomato (Solanum lycopersicum Mill.) is one of the world’s most popular vegetables. Tomato can be grown in a home garden and commercially. Tomato is widely used as a vegetable, cooking ingredient, and drink. It is one of the most popular salad vegetables consumed either in the fresh state or processed as ketchup, juice, canned, and other products [1]. Tomato can be served baked, stewed, fried, and made as a sauce with various other foods. The discovery of lycopene's anti-oxidative activity and anti-cancer function, tomatoes have gained immense popularity in recent years. [2-3].

As the population is getting higher and people tend to live healthily, the demand for tomatoes increases, especially from 2015 to 2016 in Indonesia, according to Statistics Indonesia 2016 on The National Socio-economic Survey [4]. The national consumption of tomato around the year 2016 was 1149.16 million kg, increased from the year before, which was 1065.42 million kg. When choosing the fresh tomato, consumers have some consideration before purchasing, and consumer preference plays an important role in the purchasing decision. As the people’s living condition getting improve as well as the development of social economy, consumer’s preference is also changing from quantity to quality gradually. People are paying attention to the quality, not only the appearance, color, firmness, soluble solids and not to mention its flavor of the fresh tomato [5], but also other compounds of...
nutritional interest and storage characteristics [6-7]. Therefore, it is essential to produce a high-quality tomato to meet the consumer’s expectation. The fruit quality is affected by several factors, e.g. the availability of water for the plant growth during tomato cultivation.

Water has an essential role in plant metabolism, both at the cellular level and the whole plant, therefore water is an important factor that can affect plant productivity and growth rate during cultivation. During cultivation, decrease in water availability such as water deficit, have a serious effect on plant growth, photosynthesis, solute transport, and fruit accumulation. The water deficit phenomenon often occurs due to environmental changes, besides it cannot be avoided. In response to this limited water supply, water management (irrigation) is one of the strategies that can be used to apply over the years. Water stress in cherry tomato plants grown in Spain had been studied and known to give effect to the plants in case of photosynthesis, plant growth, and crop productivity, but on the other hand it will also improve the quality parameters, such as the increase of antioxidant compound levels and higher sugar accumulation [8]. It is also reported that the water stress in plant will improve organoleptic and functional quality [9]. Restricted irrigation would enhance the aroma of materials targeted to quality markets, and also contribute to increase the efficiency of water use in agriculture [10]. The water management can be applied in high technology greenhouse for optimal plant growth by controlling the environmental factors. Crops can adapt to water stress through a series of physiological processed such as stomatal regulation and photosynthetic rapid reaction and anti-oxidase defense [11]. For greenhouse crops, fruit quality has become a main priority that requiring much care in pest and disease management. These things are performed to ensure that the yields have a certain quality with an attractive appearance. The use of greenhouse technology by modifying the conditions of the agricultural climate that are conducive to plant growth and development is beneficial not only for obtaining the desired results, but also allows for rapid harvesting, making it suitable for economic use [12].

In the high technology greenhouse, the speaking plant approach (SPA) has been studied for years. The SPA is the idea of using observed crop processes that interacted with their environmental growth as the variables to be controlled. In Japan, the environmental control in the greenhouse can be made by adding an artificial lighting and there is a tendency using online monitoring of crop responses as early warning systems to detect unintended crop stress conditions [13]. The artificial lighting in a greenhouse is used for replacing sunlight, supplementing sunlight or boosting growth and is designed in accordance with the crop’s photoperiodicity, natural day length, average hours of sunlight, solar radiation angle and intensity, and the amount of structure-induced shading. There are different grow lamps (fluorescent, metal halide, high-pressure sodium, led) available in market (in Europe) that provide blue light for foliage growth and red light for flowering and fruiting, but these are dimensioned only qualitatively and not quantitatively concerning the photosynthetic active radiation [14].

Using the high technology, the high soluble solids of fruits can be produced in the greenhouse. The high soluble solids tomato fruits can be produced using water stress treatment with an early detection technique based on the projected plant area calculated from digital color images captured by digital camera [15]. The objectives of this study were to confirm the application of automatic system for detecting the water stress and the compatibility of the water stress treatment system for producing high soluble solids tomato fruits in high technology greenhouse.

2. Research Method

2.1. Plant Material
Tomato plants (Solanum lycopersicum Mill. cv Rinka 409) were grown hydroponically with high-wire system in high technology greenhouse (1.3 ha) in Faculty of Agriculture, Ehime University (33°50’ N, 132°47’ E). The distance between the wire and the rockwool slabs where the plants grew was 3 m in height. The greenhouse has a full controlling system (temperature, relative humidity, carbon dioxide, and light intensity) to support the seasonal change and was adjusted to the real-time condition. The
sowing was done on July 22, 2018, and the tomato seedling was transplanted to rockwool slabs (0.3 x 0.25 x 0.91 m size, produced by Grotop expert, Grodan, Roermond, Netherlands) on September 6, 2018.

The greenhouse in Faculty of Agriculture Ehime University as shown in Figure 1 is a subtropical greenhouse with the type of Venlo house. This greenhouse is covered by glass and net. The net serves as a shading cover to reduce the light intensity. The irrigation system used for watering the plants inside the greenhouse is a drip irrigation system. The nutrient solution was distributed through this system. The drip irrigation system was installed on the surface of the rockwool slab with 1.5 m spacing between drip lines and 0.02 m spacing between emitters within drip lines and this system did not irrigate the whole surface. Drip irrigation was an effective way to supply water and nutrients to the root zone and it would not only save water but also increased the crop yield [16].

![Figure 1](image1)

**Figure 1.** High technology greenhouse in Faculty of Agriculture Ehime University, Japan (a) and inside high technology greenhouse in Faculty of Agriculture Ehime University, Japan (b).

The tomato plants were supplied by nutrient solutions, which were divided into 2 tanks. Tank A (200 L) contained some of the fertilizer, such as calcium nitrate (Ca(NO$_3$)$_2$) 94%, potassium nitrate (KNO$_3$) 5%, iron chelate DTPA-Fe 1%, and a small amount of Iron chelate EDTA-Fe, while Tank B (200 L) contained potassium nitrate (KNO$_3$) 21%, nitric acid (HNO$_3$) 9% monopotassium phosphate (KH$_2$PO$_4$) 6%, phosphoric acid (H$_3$PO$_4$) 20%, potassium chloride (KCl) 43%, a small amount of potassium sulfate (K$_2$SO$_4$), magnesium sulfate (MgSO$_4$), manganese sulfate (MnSO$_4$), zinc sulfate (ZnSO$_4$), borax granular, copper sulfate (CuSO$_4$), and sodium molybdate (Na$_2$MoO$_4$). The pH of the nutrient solution was 5.7 and the electrical conductivity (EC) was 2.5 dS m$^{-1}$.

2.2. **Automatic System for Water Stress Treatment**

![Figure 2](image2)

**Figure 2.** Water content measurement in the rockwool slab using water content meter (a) result for control, (b) result for water stress, (c) plunge/sensor.
Water stress condition of the tomato plant in the high technology greenhouse could be detected by measuring the water content in the rockwool slab (Figure 2) and by using visual monitoring system (Figure 3). The reduction in soil water content or from the physiological responses of the plant is one of the indicators to detect the water stress in the plant. Plants absorb root zone soil water to meet their evapotranspiration needs, and this depletes soil available water. Depending on environmental conditions and crop evapotranspiration needs, plant response to water stress can be different, as irrigation must replenish soil moisture deficit from evapotranspiration losses [17].

The water content of each rockwool slab was measured using a water content meter once a day. The water content was maintained around 20-30% for the water stress treatment and 60-70% for the control. For the water stress, if the water content was under 20%, the nutrient solution was supplied until the plant recovered to 20%. This condition can be applied automatically in the system as shown in the Figure 3. At Ehime University high technology greenhouse, SPA technology has been studied since the early 1990s, and an automatically controlled nutrient supplying system has been developed as one of these SPA technologies [15]. The automatically controlled nutrient supplying system is a technology to evaluate water stress using color images of tomato plant cultivation taken directly from the system. The illustration of the system was shown in Figure 3.

Figure 3. Automatically controlled nutrient supplying system in high-technology greenhouse in Faculty of Agriculture Ehime University Japan.

The automatically controlled nutrient supplying design, as shown in Figure 3 was using a Wi-Fi connection so that the system could work effectively. The USB camera was installed above the tomato plants and it captured the image of the tomato plants every 10 minutes. The captured image then was sent to the PC for binarization using Wi-Fi. The binarization changed the captured image into a binarized image which was the projected leaf area of the tomato plant. When the projected area measurement decreased to less than the setting, which depended on the plant and weather condition (75 – 85 %) of the maximum projected area (100%) after the last irrigation, the pump would drain the nutrient solution to the plant until the projected area recovers to 100%. The projected area could be defined according to Equation 1.
Projection area ratio (%) \(=\) projected leaf area / total area \hspace{2cm} (1)

The system for supplying the nutrient solution automatically above had been designed and proved [15] for the early detection of water stress. In this study, the system mentioned would be applied and run inside the high technology greenhouse to detect the water stress in the plant for producing a high-quality tomato fruit during cultivation.

2.3. Fruit Quality Parameter

The tomato fruit quality parameters for diameter, fresh weight, and sweetness were measured after harvesting. The measurements were conducted at the Research Center of Department of Biomechanical System, Faculty of Agriculture, Ehime University. Non-destructive methods were used for measuring the diameter and the fresh weight. While for the sweetness was measured using destructive method. The diameter was measured using a Digital Caliper Ruler (BLD-100, Niigata Seiki co., Ltd), and the fresh weight was measured using a Digital Weighing Scale (EK-300i, AND Company, Ltd). The sweetness was measured using Digital Handheld “Pocket” Refractometer PAL-1 (ATAGO U.S.A., Inc).

3. Results and Analysis

3.1. Conformity of Water Stress Detection

The SPA concept using an automatically controlled nutrient supplying system was based on the physiological status of the plants and could be used for optimal crop cultivation conditions. By using this technique, it was proved that water stress treatment could produce high soluble solids tomato fruit. Water stress detection technique based on the projected plant area could be calculated from a digital color image captured by a commercially available, inexpensive, digital still camera. The water stress detection using projected plant area of tomato plants was confirmed by measuring the projected plant area along with other plant physiological information, such as leaf temperature, water potential, transpiration rate, and photosynthetic rate [15].

The images taken from the digital camera showed images in color before they were changed into binarized images which were in black and white (Figure 4).

(a)  
(b)
Figure 4. Original image when the projected area ratio (a) 100% (b) 85% and binarized image when projected area ratio (c) 100% and (d) 85% (Shikoku Research Institute INC. database).

The original image when the projected area ratio 100% as shown in Figure 4 (a) and (c) was covered mostly by the tomato plant leaves. As the plant absorbed the nutrient solution, the solution would decrease and run out at some time, affecting the plant. As a result, the plant would give a response, i.e., wilting, which was also affect the projected area ratio. When it happened, the leaves would not fully cover the image surface taken, as shown in Figure 4 (b) and (d). The changes of projected area ratio were caused by the changes in water content of the slab. The condition of projected area ratio was also influenced by environmental condition, since it also influenced the transpiration of the plant. Higher transpiration rate without enough supply of nutrient solution caused the projected area ratio smaller [18].

Based on the system data, the treatment using the automatically controlled nutrient supplying system was conducted in 3 weeks. The water stress treatment using the system was applied on October 20, 2018 to November 9, 2018 (Table 1). The non-water stress tomato plants were also cultivated as a control.

Table 1. Water stress and control treatment in tomato plants.

| Date            | Water Stress | Control |
|-----------------|--------------|---------|
|                 | Water Content (%) | Projected area (%) | Nutrient supply time (once) | Nutrient supply (mL) | Water Content (%) | Nutrient supply time |
| October 20, 2018| 27           | 85       | 900s   | 1200   | 51     | 900s               |
| October 21, 2018| 25           | 85       | 900s   | 1200   | 63     | 900s               |
| October 22, 2018| 31           | 85       | 900s   | 1200   | 71     | 900s               |
| October 23, 2018| 25           | 80       | 900s   | 1200   | 72     | 900s               |
| October 24, 2018| 26           | 80       | 900s   | 1200   | 66     | 900s               |
| October 25, 2018| 25           | 80       | 900s   | 1200   | 66     | 900s               |
| October 26, 2018| 22           | 75       | 900s   | 1200   | 56     | 900s               |
| October 27, 2018| 30           | 75       | 900s   | 1200   | 67     | 900s               |
| October 28, 2018| 19           | 75       | 900s   | 1200   | 62     | 900s               |
| October 29, 2018| 32           | 75       | 900s   | 1200   | 72     | 900s               |
| October 30, 2018| 23           | 85       | 600s   | 800    | 64     | 900s               |
| October 31, 2018| 24           | 85       | 600s   | 800    | 61     | 900s               |
| November 1, 2018| 22           | 85       | 600s   | 800    | 60     | 900s               |
| November 2, 2018| 22           | 85       | 600s   | 800    | 65     | 900s               |
The water stress treatment using the automatically controlled nutrient supplying system (in collaboration with Shikoku Research Institute Inc.) was started from October 20, 2018, with a projected area of 85%. For the first three days, the minimum of the projected area had been set 85%, so when the projected area became less than 85%, the nutrient solution would be supplied automatically to the plant. The setting of the projected area was set according to the weather and plant condition. The water stress condition was also detected using water content measurement in the slab, which was measured every day. The water content in the slab was maintained around 20–30% for the water stress and 60-70% for the control (non-water stress tomato plant). In the water stress area, 1200 mL (900 s) of the nutrient solution was supplied once and every time the plants became wilting to some points (depended on the projected area setting). The supply of the nutrient solution was reduced at the next day once the water content measurement increased and reached more than 32%. The water stress treatment was conducted after the first harvest so that the plants were already sturdy. While for the control plant, 1200 mL (900 s) was supplied every day.

| November 3, 2018 | 20 | 85 | 600s | 800 | 65 | 900s |
|------------------|----|----|------|-----|----|------|
| November 4, 2018 | 17 | 85 | 600s | 800 | 64 | 900s |
| November 5, 2018 | 84 | 85 | 600s | 800 | 72 | 900s |
| November 6, 2018 | 72 | 85 | 300s | 400 | 74 | 900s |
| November 7, 2018 | 63 | 80 | 300s | 400 | 64 | 900s |
| November 8, 2018 | 55 | 80 | 300s | 400 | 64 | 900s |
| November 9, 2018 | 47 | 75 | 300s | 400 | 67 | 900s |

Figure 5. Tomato control plants at the left side and water stress plants at the right side.

The water stress tomato plant (Figure 5 at the right side) showed fewer leaves than the control plant (Figure 5 at the left side). As a response to water stress, plants would substantially reduce leaf water content of leaf water potential which acted as a hydraulic signal (along with chemical signals) by triggering partial closure of the stomata and reducing leaf area expansion [19]. The water stress also led to deficit soil moisture, which decreased in plant water potential and resulted in a reduction of leaf growth. The results were in agreement with other studies that water stress adversely affected physiological and photosynthetic activities of tomato plants [20].

Decrease in water availability has an immediate effect on plant growth, and processes ranging from photosynthesis to solute transport and accumulation are seriously affected. There were downward trend changes in net photosynthetic rate in water stress tomato plant [21]. Transpiration rate, changes of intercellular CO₂ concentration, stomatal conductance, instantaneous water use efficiency, and stomatal limitation were also decreasing as the water stress in plant increasing. Those physiological responses could be detected for crop water stress. The water-stressed crops have reduced evapotranspiration, and manifest other symptoms, such as leaf wilting, stunted growth, and leaf area reduction [22], tomatoes will increase their bioactive compounds without changing any quality characteristics when exposed to water stress condition [23]. This water stress condition was relatively
different with high temperature stress in root using soilless culture of tomatoes that affected bioactive compounds only when long-term stress was applied [24].

3.2. Tomato Fruit Quality of Water Stress

The water stress tomato appearance was different compared to the normal tomato. The size of the fruit was smaller, including the diameter and the fresh weight. The reduction of the fruit size was a result of the decrease in water levels in fruits. It has earlier been reported that transport of water may be reduced but not the photo-assimilates. As a result, the accumulation of the assimilates would improve the quality parameters [25].

The tomato fruits were brought to the laboratory and measured directly after harvesting. Tomato fruits that were grown under water stress treatment have known for their better qualities compared to tomato fruits grown in full irrigation. The water stress tomato, known as a high soluble solids tomato, was smaller in size, but had sweetness over 8 brix%. The tomatoes were harvested in week 17 to week 20 after transplantation to the rockwool slab. The sweetness of the water stress tomato was almost twice of the control tomato, with an average of 8 Brix %.

The water stress would affect in reduction of transpiration, but increased in fruit nutrient uptake, which resulted in the increase of soluble solids (enhance sweetness and flavor) [19]. As tomatoes ripen, there was a significant increase in their fructose and glucose contents. These sugars were the largest contributor to the soluble solids content and, in most cases, the correlation between the soluble solids and the sugars in the tomatoes was high [27]. The changes in the constituents of the soluble solids might result from a change in the glucose/fructose ratio and the organic acids in the tomatoes after harvest [28]. Soluble solids in tomato fruits are considered important, especially for tomatoes grown for processing reported that average SSC content in industrial tomatoes must be at least 5 Brix % [29]. The soluble solids content was reported as a beneficial indicator for the taste of tomatoes [30].

The size of the tomato fruits is usually indicated by their diameter and fresh weight. In general, water stress affected the diameter and weight of the fruits. According to this study, for the ‘Rinka 409’, the normal average weight of the fruit was 155.2 g, while for the water stress tomato was 66.9 g. The reason for this low weight was that the soil was dry for a long time, resulting in low fruit water content. This prolonged dryness decreased the accumulation of moisture in the fruit [18]. The decrease in fresh weight under water stress condition was caused by a calcium deficiency in plants and particularly in the developing fruits [22].

4. Conclusions

The objectives of this study were to confirm the application of automatic system for detecting the water stress and the compatibility of the water stress treatment system for producing high soluble solids tomato fruits in high technology greenhouse. The current results showed that the automatically
nutrient supplying system using visual monitoring system based on speaking plant approach technology could be used for the detection of water stress in the tomato plant, and the high soluble solids tomato fruits could be produced to fulfil consumer expectation.

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