Deficit Irrigation of Miniature Tomato Based on Estimation of Embolism Risk by Measurements of Acoustic Emission and Stress Wave at Stem

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Abstract
The drought risk evaluation of cultivating plants is the most important factor on deficit irrigation (DI). The DI, however, often causes the cavitation and embolism followed by growth inhibition of the plant. Acoustic emissions (AE) detected on a stem are associated with cavitation. Authors proposed the model in which the change in AE behavior against the change in drought stress reflects the embolism risk. Furthermore, a stress wave velocity (SWV) through stem was measured to guarantee the decrease in the drought stress of a soil-cultivated plant. In this study, the hybrid measurement of AE and SWV at stem of miniature tomato was done for controlling DI. The change ratio of SWV caused by irrigation, $R_{SWV}$, depended on the drought stress. The plants suffered severe drought stress showed that the change ratio of AE occurrence rate caused by irrigation, $R_{AE}$, was increased. The DI using $R_{SWV}$ and $R_{AE}$ was successful to maintain the yield of fruits with high sugar content.

Key words
Acoustic Emission, Stress Wave Velocity, Tomato, Embolism, Deficit Irrigation, Water Saving

1. Introduction
Irrigation is applied to avoid water deficits that reduce crop production. The crop production is required to reduce amount of irrigation while keeping high yield where water use is restricted due to economic or environmental concerns. Tomato is suitable for cultivation under dry conditions because deficit irrigation can be applied to tomato. Deficit irrigation (DI) is an optimization strategy in which irrigation is avoided when it has a scare influence on yield. Then, DI aims to maximize the productive result with smaller water amounts. Many studies on the DI to tomato have been reported because tomato is one of the most popular vegetables and it has a moderate sensitivity to water deficit [1-3]. Most of studies on DI have focused on examining the yield response to different water applications or environmental aspects. On the other hand, the drought risk evaluation of cultivating plants is the most important factor on DI to achieve a combination of water saving and high quality crops.

Fig. 1 shows a typical cross section of a stem of a miniature tomato. Most of herbaceous plants have vascular system, filled with pipe-like vascular tissue. The two main structures in the vascular tissue are the xylem and phloem. The phloem carries nutrients from the leaves down to the rest of the plant. The xylem carries water and nutrients up from the roots to the rest of the plant. The excessive irrigation (free drought stress) causes poor development of the vascular tissue followed by poor nutrients supply to the fruits. On the other hand, the poor irrigation (severe drought stress) causes the embolism in the xylem followed by growth inhibition of the plant. As water supplies become scarce, lower water potential and higher drought stress occur in the xylem. Then the cavitation phenomenon often occurs suddenly [4]. Cavitation causes an embolism followed by a considerable decrease in xylem hydraulic conductance: embolisms pose a serious obstacle to the continued uptake of water [5]. Therefore, the estimation of the embolism risk in the xylem contributes to determination of optimal irrigation for tomato growth. The embolized area in xylem is visible in a cross section of a frozen stem using Cryo-SEM [6]. Magnetic resonance imaging (MRI) is also useful to observe embolisms in the stems of transpiring grape plants [7]. Nevertheless, these are inappropriate techniques for practical use in the field because of their high cost and complexity of the environment.

Ultrasonic techniques have been applied to the study of cavitation since the 1970s. Results of those studies show that measured acoustic emissions (AE) are associated with cavitation [8]. Furthermore, authors proposed the model in which the change in AE behavior against the change in drought stress reflects the embolism risk [9]. Fig. 2 shows a simplified model in which all embolisms at xylem elements are reparable by refilling under moderate drought stress: embolism occurs temporarily. Then no refilling will occur at xylem elements if drought stress reaches a specific critical value: embolism makes a transition to permanent status. In this model, as drought stress rises from free drought stress, the number of temporarily embolized elements increases. AE (cavitation) occurrence rate also increases as shown in Fig. 3 because the repetition of cavitation and refilling occurs in all embolized elements. Consequently, the number of cavitation events would decrease when the drought stress
would reach a critical value because the embolisms remain permanently: they will not be repaired and cavitation would occur only when a new embolism appears. The AE occurrence rate therefore, shows a peak against drought stress as shown in Fig. 3. Authors studied on the AE behavior of miniature tomato plants when the drought stress was increased by cutting stem [10]. The experimental results indicated that the change ratio of AE occurrence rate caused by stem cutting corresponded to the drought stress. A parameter incorporating the change ratio of the AE occurrence rate caused by stem cutting well indicated the degree of embolism risk.

![Fig.2 Schematic of temporary and permanent embolisms in xylem](image)

**Fig.2** Schematic of temporary and permanent embolisms in xylem

**Fig.3** Model of AE behavior with drought stress of plants

Stem cutting, however, is not suitable for tomato cultivation because it is destructive method. Irrigation can be suitable method for varying a drought stress non-destructively. Irrigation will reduce the drought stress of a plant if soil is moderately dry and the irrigation water reaches a root zone. The change ratio of the AE event rate before and after the decrease in the drought stress due to irrigation, $R_{IAE}$, can be defined to assess the risk of the embolism by this model:

$$R_{IAE} = \frac{AE_{after} - AE_{before}}{AE_{before} + AE_{after}}$$  \hspace{1cm} (1)

where $AE_{before}$ and $AE_{after}$ are number of AE events detected for certain period immediately before and after irrigation, respectively. Eq. (1) defines the AE change ratio using $AE_{before} + AE_{after}$ as the denominator instead of $AE_{before}$ or $AE_{after}$ because $R_{IAE}$ can be calculated even if $AE_{before} = 0$ or $AE_{after} = 0$ (there is a possibility of $AE_{after} = 0$ at free drought stress and $AE_{before} = 0$ at severe drought stress). Hence, $R_{IAE}$ can take the value from -1 to 1. $R_{IAE} < 0$ means that the embolisms are temporary: the embolism risk is low while $R_{IAE} > 0$ means that the embolisms are permanent: the embolism risk is high as shown in Fig. 3. The proposed model suggests that the DI can be optimized by maintaining the embolisms in critical status: $R_{IAE} = 0$. This model depicted in fig. 3 simulates the embolism status of a xylem element. Nevertheless, the cavitation events from a number of xylem elements near the measurement point actually are measured as acoustic emissions by the AE sensor. The critical point in fig. 3 means the limit of drought stress under which the plant could maintain the transpiration and the photonic synthesis even if the permanent embolisms exist. Hence, it can also represent the average embolism status of the xylem elements at certain area in a stem. Thus, it is reasonable that Eq. (1) can be applicable to an actual AE measurement at a stem of a plant.

A combination of soil cultivation and drip irrigation is used for DI of tomato. Drip irrigation, unfortunately, does not guarantee the decrease in the drought stress of a soil-cultivated plant. The irrigation will result no influence on the drought stress if the soil is fully wet. The irrigation water will not reaches the root zone if the soil is completely dry. The detection of change in drought stress must be needed for DI using $R_{IAE}$. One possible idea is to measure the velocity of a stress wave transmitted through stem. Authors already studied on correlation of stress wave velocity transmitted through stem with stem structure of miniature tomato [10]. The change of drought stress of a tomato should influence on the stress wave velocity (SWV) though the correlation of SWV with the drought stress of the stem has not been studied. The wave velocity, $v$ propagating in solids depends on the elastic modulus, $E$ and the density, $\rho$ of the solid.

$$v = \frac{E}{\sqrt{\rho}}$$  \hspace{1cm} (2)

Higher drought stress results stronger wilting of herbaceous plants such as tomato. Wilting of herbaceous plant corresponds to dropping the apparent elastic modulus of the stem [11]: the SWV should be decreased. Hence, the change ratio of SWV before and after the irrigation could be criterion to decide whether the drought stress dropped due to the irrigation.

In this study, both of AE and stress wave at stem of miniature tomato were measured to verify the effectiveness of the model mentioned above. The decrease in the drought stress was judged using the change ratio of SWV and then the embolism risk was evaluated using $R_{IAE}$. Finally, the evaluation of the embolism risk was applied to DI for miniature tomato cultivation and the possibility of optimization of DI using this technique was discussed.

2. Experimental Procedures

2.1 Materials

Potted miniature tomato (Lycopersicon esculentum Mill. ‘Chika’, Takii Seed) plants were used for experiments.
Pots with 27 cm height and 33 cm diameter were filled with a soil mixture of peat moss, perlite, ash, and fertilizer. Seedlings were transplanted in the soil. The plants had been grown with an artificial light irradiance from a high-pressure sodium lamp (FEC Sunlux Ace NHR220LS, Iwasaki Electric). The lighting intensity was set to 240 µmol·m⁻²·s⁻¹ at the base of the shoot; the lighting cycle ran 12 h light per day. The temperature was set at 24 and 20 °C for day and night, respectively. The drip irrigation was applied to the pots every day at 1 h before night with one dripper installed at 2-3 cm from a stem base for a pot. Seven types of dripper were selected: the amount of injected water of each dripper was 120, 240, 360, 450, 570, 680 and 800 ml at an irrigation. The well-grown plants a month after seedling transplanting were examined for the measurement. All lateral shoots were removed as they appeared during the measurement and the plants were pinched above the third truss with two true leaves over the truss. Two pots were examined for each condition of irrigation control (the irrigation conditions are described later).

2.2 Measurements

The tension meter was used to measure soil water potential (SWP) [12]. The SWP describes the difference between the free energy of soil water and that of pure water in a standard reference state. It is widely used to determine the amount of water available from soil. It was located at 20 cm depth and 7-8cm distance from the stem base and the dripper for each pot. The value of the pressure gauge was observed manually at daytime (5-7hr from irradiation start).

The stress waves were transmitted and received on a primary stem of a miniature tomato. The measurement procedure of SWV was described in a prior work [10]. A pair of piezoelectric vibration plates of 12.5-mm-diameter was used for a transmitter. The step like wave with 20 V (peak to peak) was applied to the transmitter to generate vibration. The stress waves in the stem was generated by the vibration of the transmitter and detected by the receiver. A piezoelectric AE sensor with 300 kHz of resonance frequency (M304A; Fuji Ceramics Corp.) was used for the receiver. The washer was attached 80-120 mm above the base of the shoot as shown in Fig.4. The transmitter generated the complicated vibration because the input signal was step like wave. Fig.5 shows the typical waveforms of the detected waves and the wavelet spectrum of 10 kHz. The wavelet spectrum of 10 kHz had separated peaks of several modes most clearly of other frequency in this study although the wavelet spectrum of 5 kHz was used for the calculation of SWV in the prior work [10]. The some peaks observed in Fig. 5, however, often disappeared or overlapped with other peaks as the drought stress of the plants increased. The highest peak (H in Fig. 5), therefore, was used for the calculation of SWV because it always could be separated with other peaks and shifted slightly after the irrigation as shown in Fig. 5. The transmitter was installed at one pot for each irrigation condition and SWV was measured at interval of 6 min. Then, the change ratio of SWV, \( R_{SWV} \), due to the irrigation was calculated as following.

\[
R_{SWV} = \frac{v_{after} - v_{before}}{v_{before}} \tag{3}
\]

where \( v_{before} \) and \( v_{after} \) are average value of SWV measured for 2hr immediately before and after irrigation, respectively.

![Fig.4 Experimental setting for measurement of AE and SWV of stem of miniature tomato](image)

![Fig.5 Typical waveforms of signal and wavelet spectrum for the detected stress waves at stem](image)

The two AE sensors (M304A; Fuji Ceramics Corp.) were attached at the stem of the plant for each pot. The nearest sensor from the transmitter was also used for the SWV measurement as mentioned above. All sensors were clamped under a compression load that was less than 2 N. The AE signal was amplified using a head amplifier and a pre-amplifier (55 dB total gain of this system). The AE sensor has a resonance frequency of 510 kHz; a ninth-order band-pass filter (50–500 kHz) was used for signal processing. Then only AE data greater than 3 mV at output.
were considered for analyses. Measured AE waveforms were transferred into a personal computer via Ethernet. Therefore, the dead time at AE acquisition was 3 s. That time is longer than that of commercial AE measuring systems, but it is acceptable for this experiment because the AE counts per hour were fewer than a hundred. Total value of AE events detected by all AE sensors was used for the calculation of $R_{IAE}$. The $AE_{Inf} \text{ and } AE_{High}$ in Eq. (1) was set to be number of AE events detected for 2 hr immediately before and after irrigation.

The SWP was set to be number of AE events detected for 2 hr under S condition. The dripper was changed to larger type mentioned above. The SWP was used for DIW control 800 ml for each pot using the several types of dripper as selected for this study. The daily amount of the irrigation was 120, 240, 360, 450, 570, 680 and 800 ml for each pot using the several types of dripper as mentioned above. The SWP was used for DIW control under S condition. The dripper was changed to larger type by one step when the average value of SWP of two pots became lower than -35 kPa.

On the other hand, the deficit irrigation was done under H1 and H2 conditions by the combination of $R_{IR}$ and $R_{IAE}$. Firstly, the average values of $R_{IR}$ and $R_{IAE}$ for last three days, $\bar{R}_{IR}$ and $\bar{R}_{IAE}$ were calculated to improve the reliability. The two ultimate situations were assumed for the determination of the irrigation control. In the first situation, the soil was severely dried and the embolism risk was so high that the plant could not repair any more embolisms. The amount of irrigation apparently must be increased in the first situation. This study assumed that the first situation occurred when $\bar{R}_{IR} \geq 1 \%$ and $\bar{R}_{IAE} > 0$ for H1 condition while $\bar{R}_{IR} > 1 \%$ and $\bar{R}_{IAE} > 0$ for H2 condition. Then DIW was increased changing the dripper to larger type by one step. In the second situation, the embolism risk was low and the soil was so wet that the drought stress of the plant would not be raised much until next irrigation. The amount of irrigation apparently should be decreased in the second situation. This study assumed that the first situation occurred when $\bar{R}_{IR} < 10 \%$ and $\bar{R}_{IAE} < 0.1$ for H1 condition while $\bar{R}_{IR} < 1 \%$ and $\bar{R}_{IAE} < 0.1$ for H2 condition. Then, DIW was decreased changing the dripper to smaller type by one step. Once the dripper was changed, the DIW was kept to same level for three days because $\bar{R}_{IR}$ and $\bar{R}_{IAE}$ were the average of the measured values for three days.

3. Results and Discussions
Fig. 6 shows the behavior of the average SWP and the total amount of irrigation water (TIW). The SWP widely varied from day 0 to 10 under S irrigation condition because DIW was relatively small. The water tension indicated by the tension meter will not reduce unless the irrigation water does not reach the bottom of the pot. The water tension suddenly jumped up once the irrigation water reached the bottom of the pot. The value of SWP became stable and had maintained higher than -20 kPa after day 20 because the DIW gradually increased.

The SWP extremely dropped under H1 and H2 conditions because of deficit irrigation. There is not clear difference of the SWP behavior between H1 and H2 conditions although the threshold of $R_{IR}$ for H1 condition was higher than that for H2 condition. The average values of SWP of whole measurement period (60 days) were -22.4, -42.2 and -44.0 kPa for S, H1 and H2 conditions, respectively.

Fig. 7 shows the typical behavior of the stress wave velocity for three days (day 21 to 23). The irradiation did not influence on the drought stress on the plants under S condition because soil was wet well; the drought stress was nearly free. Consequently, Neither the irrigation and the light irradiation (day and night) did not change SWV. On the other hand, the SWV was gradually decreased in daytime and suddenly raised by the irrigation under H1 and H2 conditions. Such a behavior was obtained by the
measurement of the stem diameter change: the stem was contracted at daytime due to transpiration [9]. Thereby, the velocity of the stress wave apparently corresponded to the wilting of the plants though the wave mode used in this study was unknown.

Fig. 8 shows the behavior of $R_{IV}$ under S, H1 and H2 conditions. The DI (H1 and H2 conditions) apparently increased $R_{IV}$. The $R_{IV}$ of H1 was roughly higher than that of H2 because the irrigation was restricted until the value of $R_{IV}$ became higher than 10 %. Eventually, the average value of $R_{IV}$ for whole experimental period was 0.3, 9.0 and 1.4 % for S, H1 and H2 conditions, respectively. Thereby the drought stress of H1 condition was highest of those of all conditions because higher drought stress results larger wilting.
Fig. 9 shows the typical behavior of the AE event rate for three days (day 21 to 23). The AE event rate of S condition was much lower than those of other conditions because the drought stress was too low to induce the cavitation in the xylem of the plants. The behaviors of the AE event rate for H1 and H2 conditions reveals that the most of AE occurred in daytime because the transpiration increased the water tension in the xylem which induced the cavitation and embolism. It is worth noting that the difference of AE event rate between daytime and nighttime under H2 condition was bigger than that under H1 although the $R_{AE}$ behavior revealed that the drought stress of H1 condition was higher than that of H2. This result suggests that the drought stress of condition H1 was so high that the transpiration was restricted because the density of permanent embolisms was increased. Fig. 10 reveals that the $R_{AE}$ behavior is another evidence that the drought stress of H1 condition was higher than that of H2. The value of $R_{AE}$ for H1 condition was rapidly increased for a week from the beginning of the measurement. It was gradually decreased from day 9 and fluctuated around zero after day 22 while the $R_{AE}$ for H2 condition mostly showed the negative value. As a result, 74% of $R_{AE}$ data indicated that the value for H1 condition was higher than that for H2 condition. The proposed model as mentioned in chapter 1 suggests that the plants under H1 condition often suffered severe drought stress and eventually the density of permanent embolism was increased: the value of $R_{AE}$ was positive. On the other hand, the value of $R_{AE}$ for H2 condition was rarely positive after day 18: the most of embolisms were temporary though the SWP was as low as that of H1 condition. As a result, the average values of $R_{AE}$ for whole experimental period were 0.04 and -0.16 for H1 and H2 conditions, respectively. The DI under H2 condition, therefore, seems to be successful for preventing the embolism risk.

Table 1 Summary of TIW, SWP, number of fruits and surgar content after measurements

<table>
<thead>
<tr>
<th>S</th>
<th>H1</th>
<th>H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of irrigation [L]</td>
<td>98.2</td>
<td>41.8</td>
</tr>
<tr>
<td>Average soil potential [kPa]</td>
<td>-22.4</td>
<td>-42.2</td>
</tr>
<tr>
<td>Number of fruits</td>
<td>79</td>
<td>39</td>
</tr>
<tr>
<td>Average sugar content</td>
<td>10.0</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Table 1 shows the total amount of irrigation water (TIW), SWP, the number of fruits and the average sugar content of plants cultivated under S, H1 and H2 conditions. The plants under S condition suffered some degree of drought stress because the fruits had high sugar content (more than 8 for high sugar tomato) though TIW of S condition was much larger than those of other conditions. The fruits for H1 and H2 conditions also had high sugar content. The number of fruits of H1 condition, however, was significantly decreased. It is obvious that the plants suffered severe drought stress under H1 condition. In contrast, the number of fruits of H2 condition nearly equaled to that of S condition. Fig. 8 reveals that $R_{AE}$ behavior could indicate how severe drought stress a plant has received for H1 condition in comparison with H2 condition. On the other hand, it is worth noting that the average values of $R_{AE}$ for whole experimental period reflected the difference of the number of fruits between H1 and H2 condition while there was not clear difference of SWP. Furthermore, the measurement of $R_{AE}$ behavior is required for the estimation of the embolism risk of the plant though the difference of $R_{AE}$ behavior for two conditions in Fig. 10 was not clear in comparison with $R_{IV}$ behavior in Fig. 8. Consequently the results in this study suggest that the DI using $R_{IV}$ and $R_{AE}$ can be more effective for water saving than that using SWP. DI using $R_{IV}$ and $R_{AE}$, however, has some problems to solve for the practical use. The of DIW was decreased when both of $R_{IV}$ and $R_{AE}$ were low in this study. There is no guarantee that the drought stress was decreased by the irrigation when $R_{IV}$ was low. The hybrid measurement system used in this study was too expensive to apply for the practical use. Hence, The new irrigation method that drought stress is surely decreased is needed to estimate the embolism risk without measurement of SWV.

4. Conclusions

The hybrid measurement of AE and SWV at stem of miniature tomato was done for controlling the deficit irrigation. The change ratio of SWV caused by irrigation, $R_{IV}$, depended on the drought stress because it was increased with the decrease in amount of irrigation water. The plants suffered severe drought stress showed tendency that the change ratio of AE occurrence rate caused by irrigation, $R_{AE}$ was higher than the others. The DI using $R_{IV}$ and $R_{AE}$ was successful to maintain the yield of fruits with high sugar content. These results can conclude that drought stress is surely decreased is needed to estimate the embolism risk.

Nomenclature

$AE_{before}$ AE events detected for certain period immediately before irrigation [-]

$AE_{after}$ AE events detected for certain period immediately after irrigation [-]

$R_{AE}$ Change ratio of AE event rate before and after decrease in drought stress due to irrigation [-]

$R_{IV}$ Change ratio of SWV [-]

$v_{before}$ Average value of SWV measured for 2hr immediately before irrigation [m/s]

$v_{after}$ Average value of SWV measured for 2hr immediately after irrigation [m/s]

Abbreviations

DI Deficit irrigation

DIW Daily amount of irrigation water [L]

SWP Soil water potential [Pa]
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References