REAL-TIME COMPARISON OF SEVERAL TRANSPIRATION METHODS FOR ESTIMATING GREENHOUSE VENTILATION RATE VIA WATER VAPOUR BALANCE METHOD

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PERBANDINGAN METODE PENGUKURAN TRANSPIRASI UNTUK MENGHITUNG LAJU VENTILASI GREENHOUSE DENGAN METODE KESEIMBANGAN UAP AIR

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DOI: https://doi.org/10.356.33/inmateh-63-09

Keywords: *transpiration rate, electronic weighing device, sap flow, water level, flow rate, water vapor balance method*

ABSTRACT

Transpiration rate is an essential factor in the water vapor balance method for estimating the ventilation rate in a greenhouse continuously. Several methods of transpiration measurement, i.e., electronic weighing device (Control), the sap flow measurement (SF), water level measurement (WL), and water flow rate measurement (WF) tested and evaluated on tomato crops in a naturally ventilated greenhouse. The objective was to compare these methods and establish the most affordable one to be used in a greenhouse condition to determine the ventilation rate using the water vapor balance approach. Results obtained with the SF particularly have a strong correlation and are not statistically different from the Control (r=0.89). The WF method gave good results and reliable for predicting the total of transpiration in the greenhouse. However, in our conditions, this method generally had a lag time of the transpiration rate in a short time interval basis (minute and hourly). But it had an excellent predicted transpiration rate in daily evapotranspiration. The WL suffered weak agreement to the Control due to the scattering data. It was affected by the very high sensitivity of the device, and it is not recommended to use on the farm level, like in a greenhouse. It appears that measurements with the control and the SF could be considered for monitoring the ventilation rate in the greenhouse using a water vapor balance technique.

ABSTRAK

Transpirasi merupakan faktor yang sangat penting untuk menghitung laju ventilasi dengan metode keseimbangan uap air di dalam greenhouse. Beberapa metode pengukuran transpirasi tanaman, diantaranya: metode timbang elektronik (Kontrol), Sap flow (SF), pengukuran muka air (WL), dan pengukuran laju aliran air (WF), telah diujikan dan dievaluasi pada tanaman tomat di greenhouse dengan ventilasi udara secara alami. Tujuan penelitian adalah untuk membandingkan semua metode tersebut dan menetapkan jenis alat yang sesuai untuk menghitung laju ventilasi dengan metode keseimbangan uap air. Hasil menunjukkan bahwa metode SF memiliki hubungan korelasi yang sangat bagus dan tidak berbeda secara statistik dengan Kontrol (r=0.89). Metode WF memberikan hasil yang cukup baik dan mampu mengukur laju transpirasi di dalam greenhouse. Namun, metode ini secara umum diperoleh adanya waktu jeda dalam pengukuran transpirasi untuk interval waktu pengukuran yang singkat (per menit dan jam), tetapi metode tersebut dapat mengukur laju transpirasi tanaman harian. Sedangkan metode WL mengalami korelasi yang rendah terhdap Kontrol disebabkan oleh penyebaran data. Hal ini dipengaruhi oleh tingkat sensitivitas alat tersebut, dan alat ini tidak direkomendasikan untuk penggunaan di dalam greenhouse. Metode Kontrol dan SF dapat dipertimbangkan untuk keperluan monitoring laju ventilasi di dalam greenhouse dengan metode keseimbangan uap air.

INTRODUCTION

Monitoring the photosynthetic rate of plants by the CO_2 balance method requires precise measurement of greenhouse ventilation rate.

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Previous studies indicated photosynthesis using the CO_2 balance method with short time interval measurement from 1 to 15 min *(Chalabi and Fernandez, 1994; Zekki et al., 1999; Takakura et al., 2017*). It certainly requires the ability of the sensor to monitor the ventilation rate in real-time properly. One of the methods to estimate the ventilation rate is the water vapor balance method (WVB), as mentioned by *Li et al. (2012),* and *Mashonjowa et al. (2013).* The primary source of water vapor in the greenhouse is from leaf transpiration. *Tusi and Shimazu (2020)* reported that the reliability of WVB method depends on the accuracy of short-term transpiration measurements. Hence, an accurate measurement of transpiration is needed to quantify water vapor present in the greenhouse for predicting the ventilation rate based on this technique.

There are various types of transpiration recording devices used by greenhouse engineers, i.e., electronic weighing balance *(Boulard and Draoui, 1995; Kittas et al., 2002; Li et al., 2012)*, sap flow sensor *(Mashonjowa et al., 2010)*, water flow sensor *(Harmanto et al., 2006).* There is another method that has been developed by *Shimomoto et al. (2020)* using an open bottom chamber to monitor photosynthesis and transpiration. Among the different methods for direct measurement of the transpiration rate, the electronic weighing device is standard and has been widely used in a Dutch commercial greenhouse *(De Koning and Tsafaras, 2017).* It measures the changing of fresh weight of plants either in 1 plant or several plants in a device per time unit, i.e. 4 plants/device *(Boulard and Draoui, 1995),* and 3 plants per device *(Kittas et al., 2002).*

Laperen and Madery (1994) promoted a new weighing lysimetric system to measure transpiration and water uptake simultaneously on one plant in short time intervals (min). The previous study showed that the interval time for measuring ventilation rate based the WVB was 10 min, 1 h, and daily, as mentioned in *Kittas et al. (2002), Boulard and Draoui (1995),* and *Harmanto et al. (2006),* respectively. Hence, this technique can monitor quick responses to changing environmental conditions.

In terms of the sap flow technique, it is measured based on heat flow. This method is ideally suited to applications requiring routine determinations of plant water use, and it is very useful in studies of plant responses to environmental conditions in either the field or laboratory (*Smith and Allen, 1*996). Also, the sap flow had a close correlation with the leaf area index *(Cohen and Li, 1996)* and suggested that the results were free of external environmental noise.

Mashonjowa et al. (2010) estimated the ventilation rate using water vapor balance by the sap flow sensor. They observed water vapor in a large greenhouse (1,267 m^2) via two the sap flow sensors only recorded every 5 s and averaged over 30 minutes. Furthermore, *Harmanto et al. (2006)* recorded data on an hourly basis and average over nine h or daily ventilation rate (daylight). This technique allows us to measure water consumption either in one row/bed system or one greenhouse. It is different from the previous method that measured only one or several plants per device. However, plant physiological measuring is highly inhomogeneous in a greenhouse system, which means that a large number of sensors will be required for getting reliable means. So far, no sensors for data logging right on the plant have been used in practical horticulture due to limited information, especially for monitoring of ventilation rate value using the WVB approach in a greenhouse system. There is no information about the suitable transpiration device for estimating the ventilation rate using the water vapor balance method. It has been mainly affected due to the high cost of such measuring instruments and the difficulty of attaching them to the plant. This paper presented a comparison and evaluation of the applicability of different direct transpiration devices for use in greenhouse experiments to predict and monitor the ventilation rate in real-time. The research aimed to compare and evaluate the other method of transpiration measurement either in the technical aspect and interval time measurement capability; also, to provide recommendations or suggestions that could be used for monitoring the ventilation rate using the WVB technique.

MATERIALS AND METHODS

For computing the transpiration rate, the experiment was conducted in a naturally ventilated greenhouse to generate water vapor during the day time in a single-span experimental greenhouse at a research field site of Faculty of Applied Biological Science, Gifu University, Japan. The greenhouse was made of glass (glasshouse) with dimensions of 3.25 m × 5.00 m × 2.80 m. It had a supported roof and double flap side ventilations, which was covered with screen-net materials (pore size 0.4 mm and porosity 52.2%).

The greenhouse was occupied by mature tomato crops (*Lycopersicon esculentum* Mill., variety 'Momotaro'), cultivated on 14 modified Wagner pots with a volume of 10 L (one plant per pot) filled with light sandstones (diameters ranging from 1 to 5 mm) and supplied with hydroponic nutrient solutions (EC= 1 dS

m^{-1} and pH range of 5.5–6.5) in the lower part of the pot system with a maximum water level of 10 cm (capillary irrigation system). A net area of surface pot was 180 cm^2, and the growing medium on the pot system was covered with plastic mulch.

The transpiration rate (g h^{-1}) of cultivated tomatoes in the greenhouse was measured by the different methods, as presented in Table 1. The method as control was using an electronic weighing device (Model SW-15KS, A&D Company, Japan) with an accuracy of 2 g (Fig. 1a). The control measurement was compared with other methods, i.e., the Sap flow measurement (SF), water level measurement (WL), and water flow meter device (WF). The SF and WL were compared with the control, but the WF was compared with the SF. All measurements were conducted and recorded every minute during the daytime, then, a 15-minutes interval averaging data basis due to the time lag of direct methods for measuring transpiration. All the above measurements were recorded in a data logger (CR1000, Science Campbell, USA).

The transpiration from the Control device was computed as below equation:

$$Tr = \frac{W_{(t-1)} - W_{(t)}}{dt}\ x\ 60 \qquad (1)$$

where T_r is transpiration rate (g h^{-1}); $W_{(t-1)}$ is pot weight before t time of measurement, and $W_{(t)}$ is pot weight in t time of measurement; d_t is the time interval (15 minutes); 60 is converter coefficient from minute to hours.

The Sap Flow measurement

The SF rate (Fig. 1b) was measured continuously at the base of the stem of selected tomato plants with Dynagage Sap Flow sensors (Model SGA13-WS, Dynamax Inc., Houston, USA), installed according to the operation manual. It was enclosed in a thermally insulated sheath and wrapped around the stem to prevent direct sunlight and adverse environmental effects. It works based on the energy balance method, where the amount of heat carried by the SF is converted into real-time sap flow in grams per hour. Even the stem of the plant is heated, but it is non-intrusive and not harmful since the plants are heated 1 – 5°C.

Detailed calculation with the SF method was presented in *(Smith and Allen, 1996).* Daily observation of the SF was conducted at an interval of 1 min, a CR1000 datalogger (Campbell, Co., USA) was used to measure the SF output during the tomato growth seasons. Transpiration rate using the SF was observed in late winter until spring seasons, from March to April 2019, and compared with the control device.

Table 1

Transpiration measurement devices observation

Measurement Methods	Device	Specification	
Control (C)	Electronic weighing	SW-15KS Model Capacity max. 15kg Minimum display 2 g	A&D Company, Japan
Sap Flow (SF)	The Sap flow sensor	SGA13-WS Sensor Stem diameter= 12-16 mm	Dynamax Inc. USA
Water level (WL)	Water level measurement	FL-001 Pulse Type Level Sensor Tank pressure= -0.1 to 0.5 MPa Resolution 1 mm	Keyence, Japan
Water Flow (WF)	Water flow rate measurement	FD-XS8 Clamp-On Micro Flow Sensor Tolerance: + 8mL Rate= 0 – 8000 mL/min	Keyence, Japan

Water Level Measurement Devices

The water level device was measured by a water level sensor (FL-001 Pulse-type level sensor, Keyence, Japan) continuously (Fig. 1c). It measured the water level of nutrient solution on the below part of the pot system using the stick with an accuracy of 1 mm. Decreased water in the pot system was recorded in 1 min interval basis, then averaged every 1 hour. The transpiration rate was calculated by observing the changes in water level over the time interval of measurement (Eq. 2). The transpiration measurement period was observed in the fall season, between October – December 2019. Also, it was compared with the control device.

$$Tr = \frac{[WL_{(t-1)} - WL_{(t)}]}{dt\ .\ 10} \times \rho \times A_p \qquad (2)$$

Where T_r is transpiration (g h^{-1}); $WL_{(t-1)}$ is water level in the pot before t time of measurement, and $WL_{(t)}$ is water level in t time of measurement (mm); d_t is the time interval (1 h); ρ is water mass density (1 g cm^{-3}), and A_p is the net surface area of pot system (cm^2).

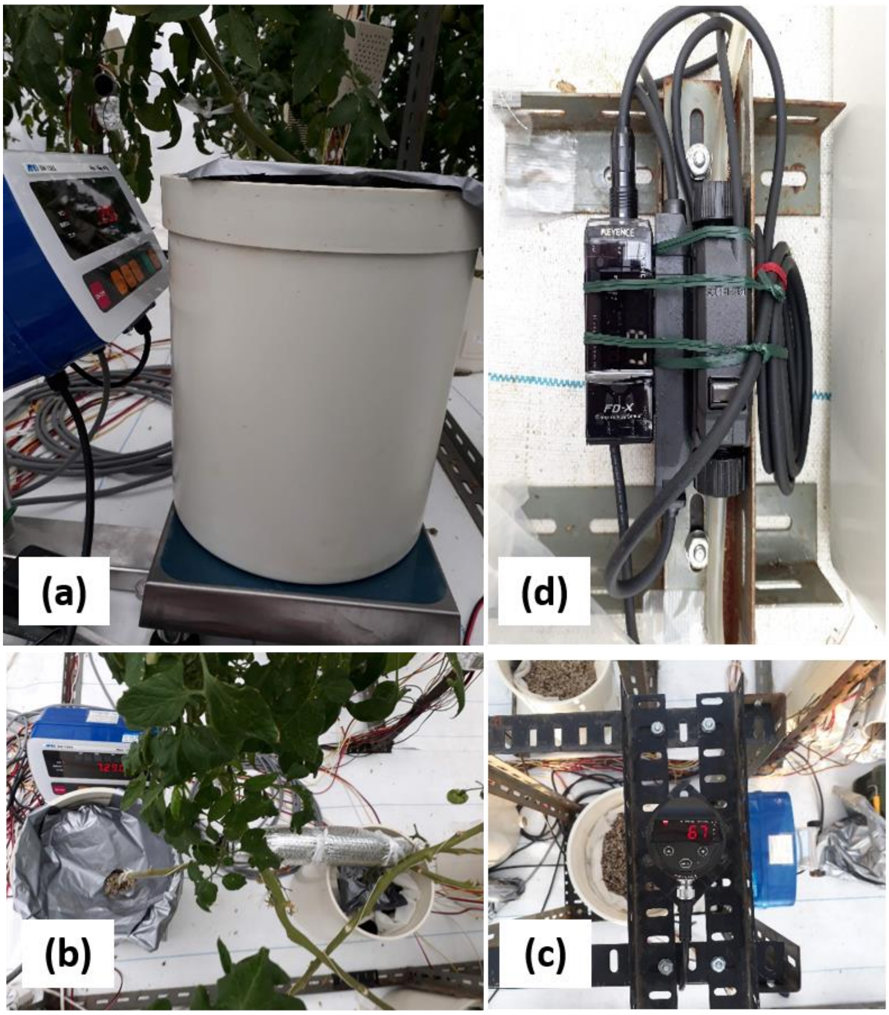

Fig. 1 - Transpiration measurement devices

(a) Electronic weighing device (Control), (b) Sap flow sensor (SF), (c) Water level sensor (WL), and (d) Water flow sensor (WF)

Water Flow Measurement Devices

For water flow measurement, it was conducted in a plastic house at a research field site of Faculty of Applied Biological Science, Gifu University, Japan. The greenhouse was covered using plastic material with dimensions of 5 m × 10 m × 3 m. The total of greenhouse floor area was 50 $m^{2,}$ and the greenhouse volume was 120 m^3. It had supported the roof and side ventilation, which was covered with screen-net materials (mesh opening 0.8 mm with porosity 62%). The greenhouse was occupied by mature tomato crops (*Lycopersicon esculentum* Mill., variety 'Momotaro'), cultivated on the two-bed system using substrate culture technique (light sandstones with a diameter ranging from 1 to 5 mm) and supplied with hydroponic nutrient solutions (EC= 1.1 – 1.3 dS m^{-1} and pH range of 5.5–6.5).

The substrate surface was covered with plastic mulch. During the measurement periods in early spring seasons 2020, and the tomato crops were cultivated at an average height of about 1.5 m. The plants were laid out 0.45 m apart in double rows on each bed, and each bed has dimension 6.0 m x 0.65 m. The total number of tomato plants was 46 plants (23 plants per bed) in the greenhouse. The nutrient solution was supplied from the water tank under the cultivation bed by capillarity, and the liquid level in the water tank was adjusted by the float liquid valve. The flow rate from the storage medium tank to the cultivation bed via the main pipe was measured using the micro-flow sensor (FD-XS8 Clamp-On Micro Flow Sensor, Keyence, Japan) attached to the outside of the pipe, as presented in Fig. 1d. The outside diameter plastic tube used 8 mm, hence the 1.27 cm diameter of the mainline should be converted to 8 mm for a measurement. This device was calibrated before applied in the greenhouse, and it has good performance with the measurement based on the volumetric method.

Because it was cultivated on bed systems (not in pot system), it had compared with the SF technique after the SF was calibrated with the Control. All data collected have been statistically analysed by linear regression between the reference method and the other methods using R software.

RESULTS

The transpiration rate of a tomato measured by a SF sensor was in the range of 10 to 150 g h-1 in the spring season. The SF had a similarly good result with the Control as close with the target line, as shown in Fig 2(a). The graph showed that the SF measurement (15-min interval) was remarkably accurate and had a strong correlation to the Control with the corresponding value of the Pearson correlation coefficient (r) of 0.89, as presented in the figure (***p = 2.2 × 10^{-6}). *Lascano et al. (2016)* reported that there were no statistical differences between hourly and daily values of sap flow measurement with the lysimetric. The measured transpiration rate by the Control was slightly higher than the sap flow sensor due to evaporation from the substrate from the pot system even if it was covered by plastic mulch. The evaporation from the growing media was too small by 6.3% from the total of evapotranspiration. Even if it was small, it should be considered to calculate the total water vapor balance method in the greenhouse for predicting the ventilation rate.

Based on the result, it can be directly used in the SF measurement for further monitoring of the ventilation rate using the WVB method. Practically, the SF device should be regularly checked and calibrated. Also, it was recommended to change the position of the sensor on stem plants to other plants.

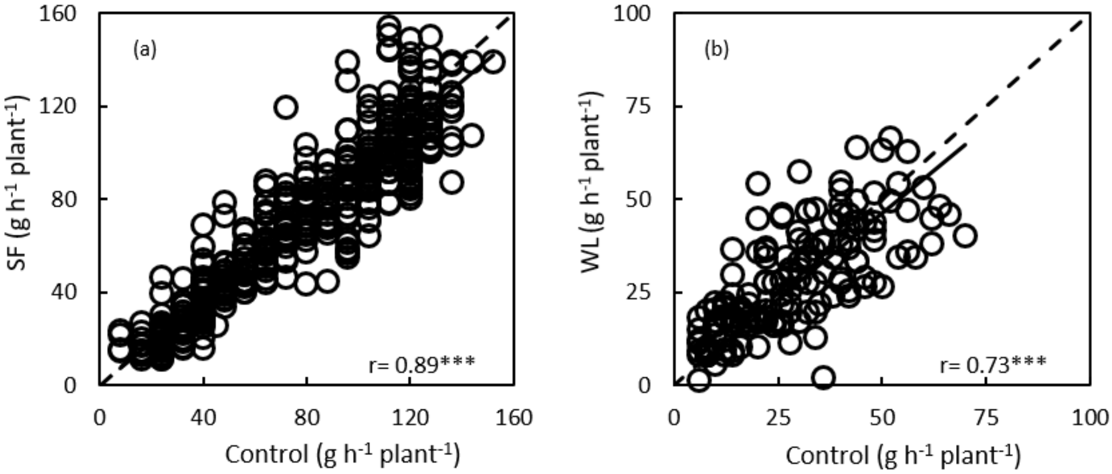

Fig. 2 - Transpiration rate correlation value between (a) the SF measurement with the Control during the spring season, March – April 2019 (n=404 data), and (b) the WL measurement with the Control during October – November 2019 (n=163 data). The r value is the corresponding value of the Pearson correlation coefficient (*p=2.2 ×10^{-16} <0.001)**

The WL measurement has slightly smaller transpiration compared to the SF because it was conducted in the fall season with lower radiation than in the spring season (data not presented), between October and November 2019, with the value from 5 to 60 g h^{-1} per plant. The WL measurement exhibited a good correlation to the Control with the r value being 0.73, as presented in Fig 1b. It was lower than the SF because there was a scattered data linearly with an increase in transpiration rate. The fluctuated data was affected by the very high sensitivity of the device to the activities in a greenhouse (shaking to the pot system during the cultivation process). Also, the low transpiration rate has influenced the accuracy due to the lag time of measurement in the short time interval measurement.

Akutsu et al. (2015) also reported that the water level with the manometer type for potted tomato plants had a time lag of measurement, whereas they refilled to maintain a certain level in the tube every 2 hr. In this observation, even the WL device accuracy of measurement is 1 mm. Still, if it is converted to a weight unit (in gram), it was found that 1 mm of precision device equals 18 g at 180 cm^2 of the pot tomato cultivation area that is used. It means that the Control (2 gr of accuracy) was higher than the WL device. It is one of the reasons why the WL suffered the lag time of the direct measurement of the transpiration rate. Contrary to the WF method, it measured the total amount of water consumption of tomato crops in the greenhouse.

During observation in March 2020 (spring season, with n=375 data), the transpiration rate varied between 50 – 150 g h^{-1} per plant. This value was the same transpiration rate as a measurement in spring 2019 by sap flow and weighing device measurement.

Fig 3a showed that the WF measurement had a lower correlation compared to the SF with r = 0.59. The water flow measurement has a lower correlation than the sap flow and the water level measurement devices.

This problem can be elucidated with diurnal changes in the transpiration rate both in a cloudy day (Fig 3b) and in a sunny day (Fig 3c).

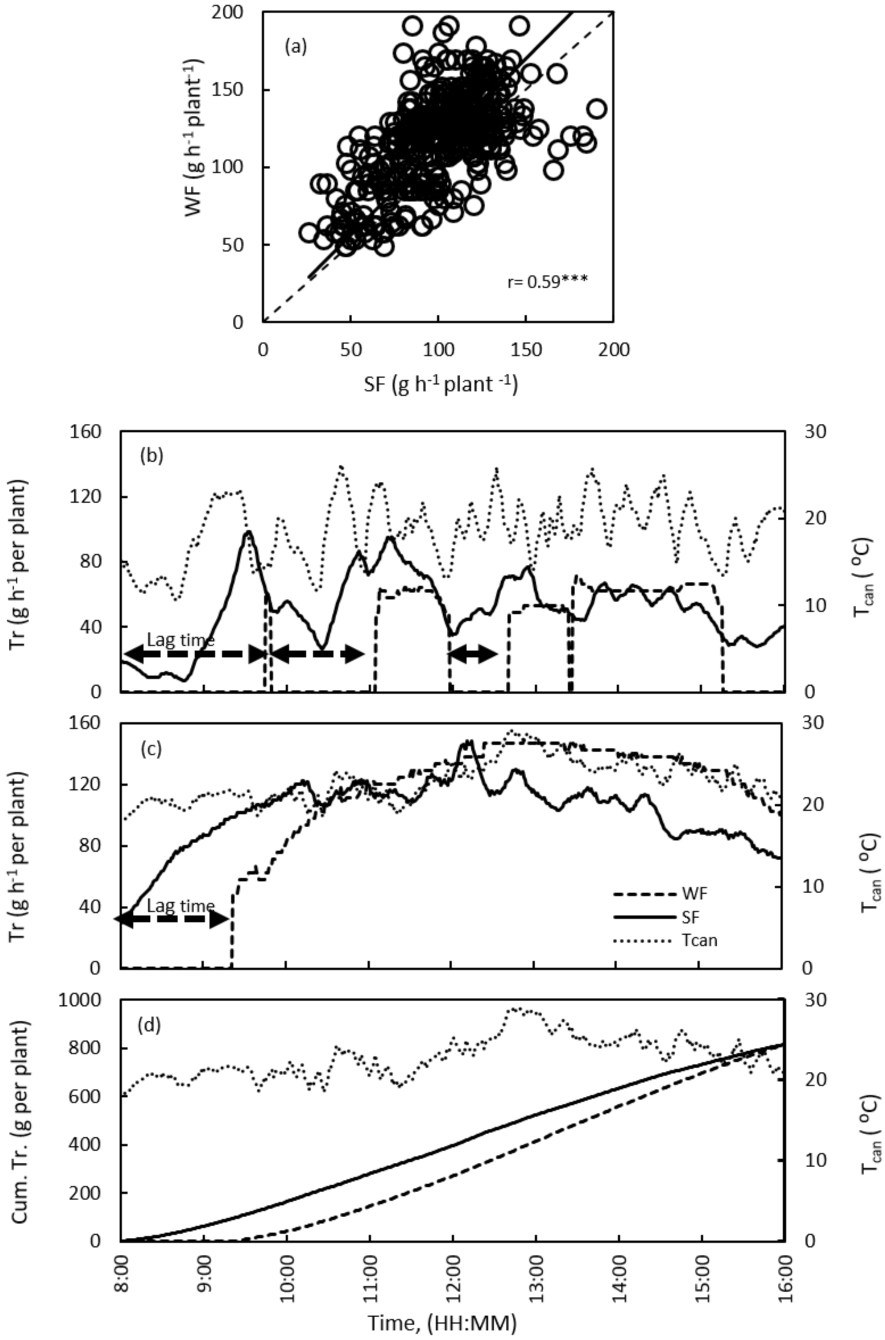

Fig 3. (a) Correlation of transpiration rate measurement between the WF and the SF measurement; b) the diurnal changes in transpiration rate during (b) cloudy day, March 5, 2020 (c) sunny day, March 6, 2020. (d) the accumulation of transpiration during the measurement day on March 6, 2020

The water flow measurement in the greenhouse experienced several time lags in the direct measurement of transpiration on a cloudy day. This condition was often encountered during cloudy conditions (Fig 3b) than when it was a sunny day (Fig 3c).

The fluctuation of transpiration data at a different time in the day should be related to the variable conditions of irradiance recorded that are related to the canopy temperature condition (Tcan). An increase of irradiance in the greenhouse caused enhancement of transpiration rate consequently.

Thus, the time lags of measurement were fewer in number in high radiation condition than lower radiation, like in cloudy condition. *Wei et al. (2020)* noted that the SF rate was primary controlled by photosynthetically active radiation (PAR) and varied with time scales. On sunny days, the time lag appeared in the morning only. After that, the transpiration rate measurement by water flow was similar to the sap flow in mid-day. However, when the transpiration rate was accumulated in the measurement day, as presented in Fig 3d, it shows the same level of total transpiration rate during the day. It indicated that the water flow measurement has a reasonably measured transpiration in daily measurement, not in a short time interval. It should be noticed that in this experiment, the water flow device measured the total of water consumption of the tomato crops supplied by a passive system with an automatic floating valve to supply water in the bed cultivation system. It might be another reason for the time lag of transpiration measurement. Further research about the implementation of the water flow device with a drip irrigation system or others should be performed.

Table 2

Transpiration measurement devices observation

Description	Transpiration measurement devices			
	Electronic Weighing (Control)	Sap Flow (SF)	Water Level (WL)	Water Flow (WF)
Measurement of time record	10-15 minutes*	per minute	hourly and daily	daily
Scale of measurement	One plant or several plants per device	One plant only	One plant or per tank	A large community of plant (per greenhouse)
Advantageous	High accuracy	Good agreement with the Control	Knowing real-time of water uptake measurement	Measuring of total water consumption in a greenhouse
Disadvantageous	Sensitive to human activities	Need calibration regularly and change position	Sensitive to human activities; time lag of measurement	The time lag of measurement
WVB technique application**	√√√√	√√√√	√√	√√

**) it depends on the accuracy level of a measurement device. It was conducted with 2 g of accuracy level.*
***) Transpiration devices recommendation for monitoring ventilation rate via the WVB method.*
(√ = not good, √√ = enough, √√√ = good, √√√√ = very good)

Overall, among the four different methods used in this study, the sap flow and an electronic weighing device (with 2 g of accuracy) were recommended for estimating the ventilation rate in the greenhouse, as needed to calculate the photosynthetic rate via CO_2 balance method. The detail of the measurement methods was presented in Table 2. It shows the advantages and disadvantageous of several different transpiration measurement devices. 2 g of accuracy level of measurement via an electronic weighing device was enough to measure transpiration rate with the time lag of measurement between 10-15 minutes. Also, it was enough for estimating the photosynthetic rate via the CO_2 balance approach. As we know, an increase in the accuracy level of measurement devices will contribute to the cost that should be paid.

Leperen and Madery (1994) observed the transpiration and water uptake by an electronic weighing lysimeter with an accuracy level of 0.03 g min^{-1} $plant^{-1}$ that may be made for short time intervals (min). The high accuracy level makes it possible to monitor quick responses to changing environmental conditions.

CONCLUSIONS

Transpiration rate could be monitored directly and continuously by the electronic weighing lysimetric and the sap flow measurement in a short time interval (minute). The measured transpiration rate via the sap flow gave a better result than the water level and water flows measurement approaches. Also, it has the same level of transpiration rate with the Control. The Control and the sap flow can be used for real-time monitoring in short time interval (per minute) compared to the water level and the water flow devices which need hourly and daily interval, respectively. The electronic weighing device and the sap flow may permit continuous real-time monitoring of the crop transpiration rate in a greenhouse, which is a primary parameter of the WVB method for estimating the ventilation rate.

ACKNOWLEDGEMENT

One of the authors (Mr. Ahmad Tusi) would like to thank the Indonesia Endowment Fund for Education (LPDP, BUDI-LN), Ministry of Finance, and Ministry of Education and Culture, the Republic of Indonesia for funding the doctoral program at Gifu University, Japan.

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